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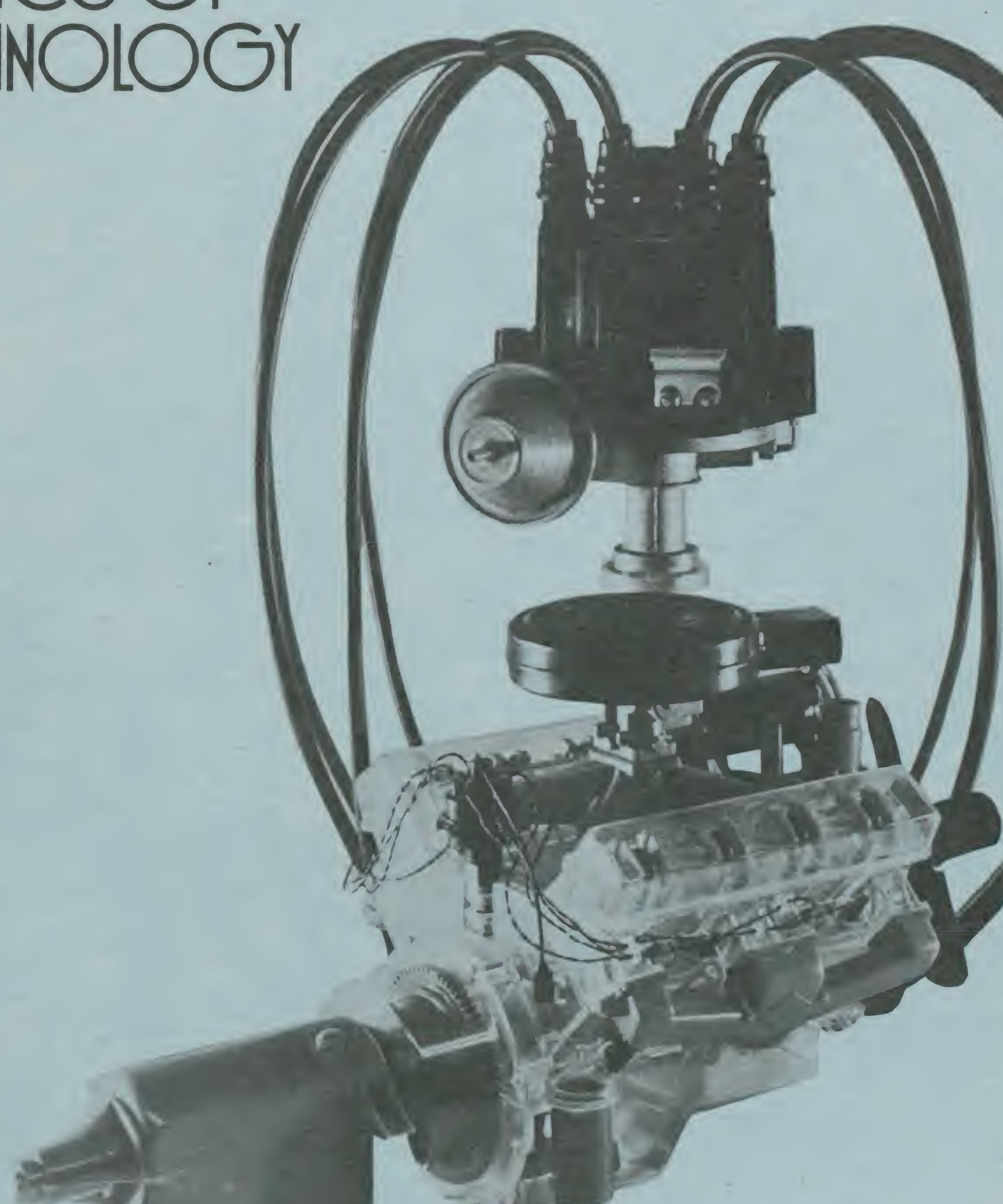

AUTOMOBILE IGNITION SYSTEM

Electricity and Magnetism.

AUTOMOBILE IGNITION SYSTEM

A Module on Electricity and Magnetism

FVCC

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Automobile Ignition System

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AUTOMOBILE IGNITION SYSTEM

PREREQUISITES

This module will use an automobile ignition system to illustrate certain principles of electromagnetism. At the end of the module, you should have a thorough understanding of the ignition system but, more importantly, the concepts and principles learned here will help you to understand many other devices which depend upon electromagnetism.

Before starting work on this module, you will need certain prerequisite skills and concepts:

1. The ability to explain electric charge, electric current, electric potential difference, electromotive force (EMF), and electric resistance.

2. Knowledge of the correct SI units for electric charge, current, resistance, and potential difference (or EMF).

3. Knowledge of how to connect a series electric circuit, containing a battery, one or more resistors, and a switch.

4. The ability to use an ammeter to measure the current and a voltmeter across a resistor to measure potential difference in a series circuit.

5. Knowledge of how to use Ohm's Law to calculate either potential difference (or "voltage"), resistance, or current, as required.

6. The ability to use a calibrated oscilloscope to measure a designated time interval or voltage for some repetitive trace produced by an electric circuit.

You may test yourself to see if you satisfy these prerequisites by taking the following test. If you can answer correctly all of the items, you are ready to begin the module. If you have trouble with one or more, get some help from your teacher or another student.

PREREQUISITES TEST

(Your instructor has the correct answers to these items in his Teacher's Guide.)

1. The following statements describe certain electrical quantities. Match each statement to the quantity to which it refers most closely.

   Statements

   A. When two different objects repel one another, two other objects attract one another. This is because they have ___________.

   B. A resistor in a circuit has a current through it. This means that, across its ends, there is a ___________.

   C. A battery maintains an electric current in a circuit until the battery is "dead." It no longer produces ___________.

   D. A conductor carrying an electric current is observed to heat up, and a potential difference is measured between two points on the wire because of the ___________ of the circuit.

   E. The amount of electric charge passing through a circuit per second is called ___________.

   Quantities

   a. EMF
   b. Potential difference (voltage)
   c. Electric charge
   d. Electric current
   e. Resistance

2. Match the correct SI unit with the quantity listed.

SI Units

A. EMF
B. Potential difference
C. Electric charge
D. Electric current
E. Resistance

Quantities

a. Coulomb (C)
b. Milliampere (mA)
c. Ampere (A)
d. Millivolt (mV)
e. Microcoulomb (μC)
f. Volt (V)
g. Ohm (Ω)
h. Farad (F)

3. Your instructor will give you two resistors, a battery, a switch, and some wire. Connect the resistors in series with the battery and switch, and leave the switch open.

4. Using the circuit you have wired for Item 3, connect an ammeter to measure the current in the circuit, and connect a voltmeter to measure the voltage across one of the resistors.

   Leave the switch open until your instructor checks your circuit. When he has checked your circuit, close the switch and measure the current and voltage.

5. Using Ohm's Law, and the values of current and voltage found in Item 4, calculate the resistance of the resistor across which you measured the voltage.

6. Your instructor will provide you with a calibrated oscilloscope and an electric circuit whose output will provide a repetitive oscilloscope pattern. Turn on the oscilloscope, make all necessary adjustments, and measure a voltage and the period of the trace, as designated by your instructor. (If you don't know how to use the oscilloscope, the appendix will provide the information you need.)

GOALS FOR SECTION A

The following goals state what you should be able to do *after* you have completed this section of the module. These goals must be studied carefully, as you proceed through the module, and as you prepare for the post-test. The example which follows each goal is a sample test item which fits the goal. When you can correctly respond to any item like the one given, you will know that you have met that goal. Answers to the items can be found immediately following these goals.

1. *Goal:* Understand under what conditions an electromotive force (EMF) can be induced in a coil of wire.

   Item: In which of the situations shown in Figure 1 would you have an induced EMF in coil 2?

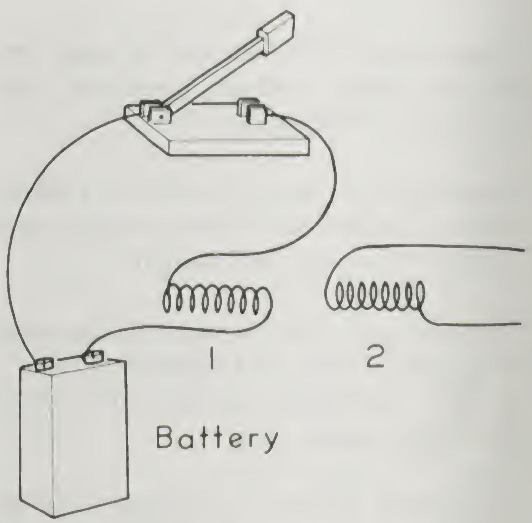

Figure 1A. Switch being opened.

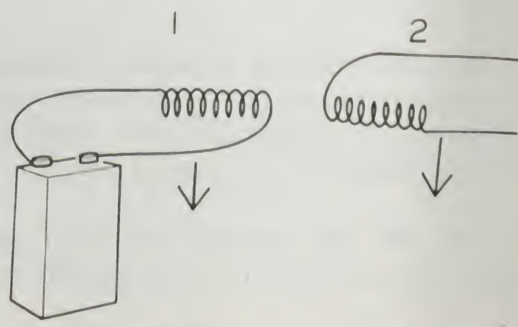

Figure 1B. Both coils moving in the same direction at the same speed.

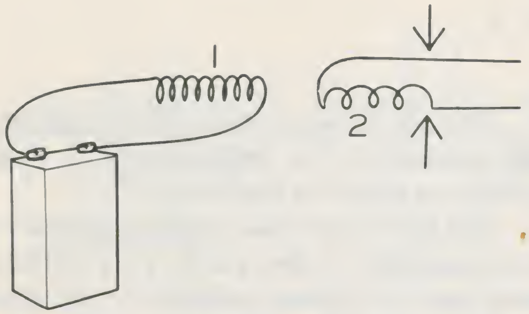

Figure 1C. Coil 2 being flattened ("squashed").

2. *Goal:* Be able to explain the functions of the following ignition system components: battery, ignition coil, breaker points, spark plug, capacitor.

   Item: What is the main function of the capacitor in the ignition system?

3. *Goal:* Understand the concept of magnetic poles.

   Item: You will be given three bar magnets, one suspended by a thread from its center. You will be required to mark the ends of all three magnets as north or south poles, using no other equipment and without untying the thread.

4. *Goal:* Be able to find the direction of a magnetic field by using a small test magnet.

   Item: Figure 2 shows two bar magnets and a small compass. What is the direction of the magnetic field at the position of the compass?

Figure 2.

5. *Goal:* Be able to predict the direction of deflection of an electron moving through a magnetic field.

   Item: In which direction will the electron shown in Figure 3 be deflected when it passes by the magnet?

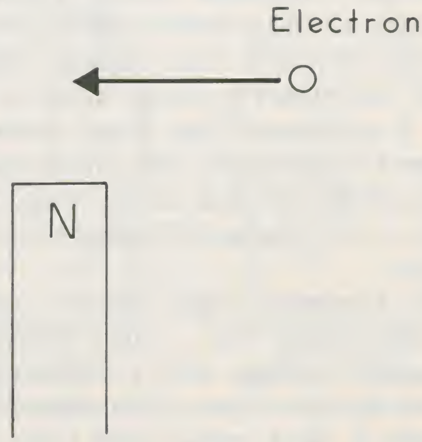

Figure 3.

Answers to Items
Accompanying the Previous Goals

1. a and c.
2. To prevent arcing across the points.
3. The suspended magnet will swing so that one end points north. That end is designated the "north pole" and the opposite end the "south pole." By bringing the ends of the other two magnets close to the north pole of the first, they can also be classified as north or south by using the rule that like poles repel and unlike poles attract.
4. Left to right.
5. Out of the paper, toward the reader.

SECTION A

THE INTERNAL COMBUSTION ENGINE

To understand an automobile ignition system, you first need to know a little bit about how an automobile engine operates. In the internal combustion engine, gasoline is mixed with air and is burned inside a *cylinder* to form a hot gas at high pressure. This gas expands and pushes a *piston,* which in turn rotates a *crankshaft.* This rotary motion is transferred to the *wheels.* The overall result is a change of the chemical energy stored in the gasoline to the mechanical energy of motion of the car.

The four-cycle engine which is used in most automobiles has a long history of development, starting with a single-cylinder engine of the type shown in the cutaway view of Figure 4. Most engines used today have four, six, or eight of these cylinders arranged along a crankshaft.

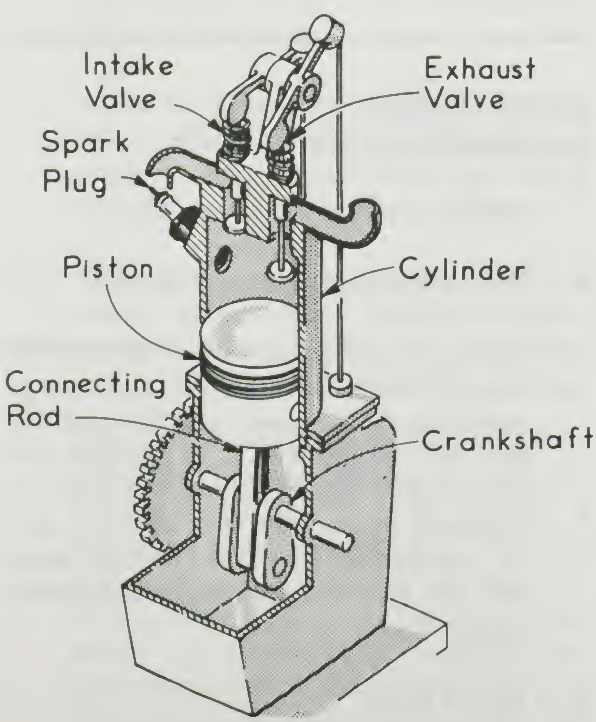

Figure 4.

The events which take place during the four strokes of the piston inside a single cylinder are shown in Figure 5.

The first of the four strokes is called the *intake stroke.* As the piston of a cylinder moves past its highest position, or *top dead center position,* the intake valve opens. The piston travels downward, as shown in Figure 5a, and draws in a mixture of tiny droplets of gasoline and air from the carburetor. The intake valve stays open until the piston has traveled almost completely downward and the cylinder is filled with a mixture of vaporized fuel and air. At the lowest point of piston travel the intake valve is closed, and the piston begins the second of the four strokes, called the *compression stroke.*

With both valves closed, as shown in Figure 5b, the fuel-air mixture is not able to escape. As the piston returns to its highest position, it compresses the mixture to about 1/8 of its original volume.

As the piston comes once again to top dead center, the valves remain closed, and the compressed air-fuel mixture is ignited by the spark plug. The piston then begins the *power stroke,* as shown in Figure 5c. The high pressure caused by the heat from burning the fuel forces the piston downward. This causes the crankshaft to turn. The amount of work delivered during the power stroke far exceeds the total work input necessary to complete the other three strokes.

The final stroke of the four-cycle engine is the *exhaust stroke.* As the piston passes *bottom dead center* upon completion of the power stroke, the exhaust valve opens. When the piston travels up on this last stroke, as shown in Figure 5d, it forces exhaust gases out of the exhaust pipe.

Each of the cylinders of an automobile engine goes through this same sequence of strokes. However the timing of the strokes differs from cylinder to cylinder. For example, in a four-cylinder engine, each cylinder is in a different stroke at a given instant, and only one is delivering power at that instant. This staggering of the sequences gives

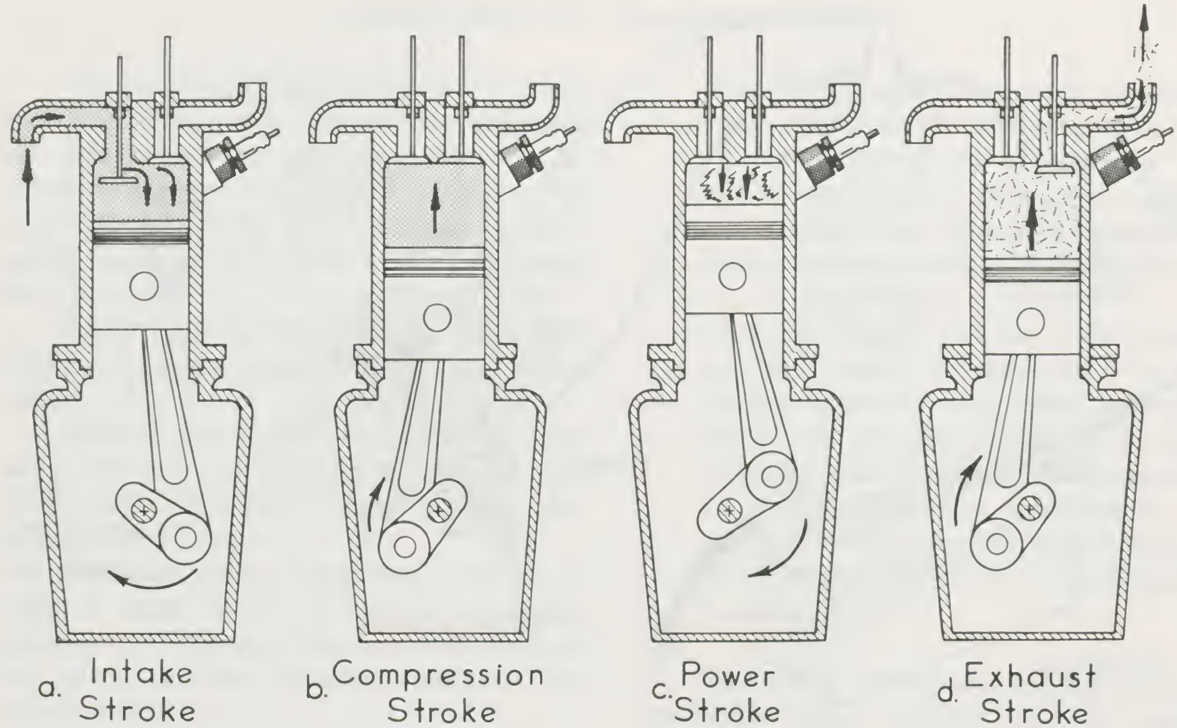

Figure 5.

a more even delivery of power to the crankshaft.

Question 1. There are engines which operate in only *two* strokes. How do you suppose that a two-cycle engine works?

It might seem that the air-fuel mixture in the cylinder should be ignited at the instant when the piston is at top dead center (TDC) on the compression stroke. This is not the case, however, because it takes time for the gas-air mixture to burn. The time required for the flame to travel from the spark plug through all of the air-fuel mixture is several milliseconds. The time required for the piston to make a stroke is not much longer than this. Therefore, to be sure that most of the fuel burns, the mixture is ignited *before* the piston reaches the top of the compression stroke. This production of a spark to cause ignition before the piston reaches TDC is called *spark advance.* At higher engine speeds, the time of piston travel is even less, and so the spark must be advanced even more.

THE IGNITION SYSTEM

The three chief functions of an automobile ignition system are:

a. To provide a spark that will ignite the air-fuel mixture.
b. To route the spark energy to the right spark plug.
c. To produce the spark in each cylinder at the right time in the cycle.

The ignition system accomplishes these things with five main components: the *battery,* the *coil,* the *distributor,* the *ballast resistor,* and the *spark plugs.* The coil takes electrical energy at low voltage [e.g., 12 volts (V)] from the battery and changes it into electrical energy at high voltage (e.g., 20,000 V). The distributor switches the coil on and off at the right times, and it routes energy to the plugs. The plugs then ignite the air-fuel mixture. The entire system, including the balast resistor which prevents too-high currents, is shown in Figure 6. At this point you may familiarize yourself with the ignition system by completing Experiment A-1.

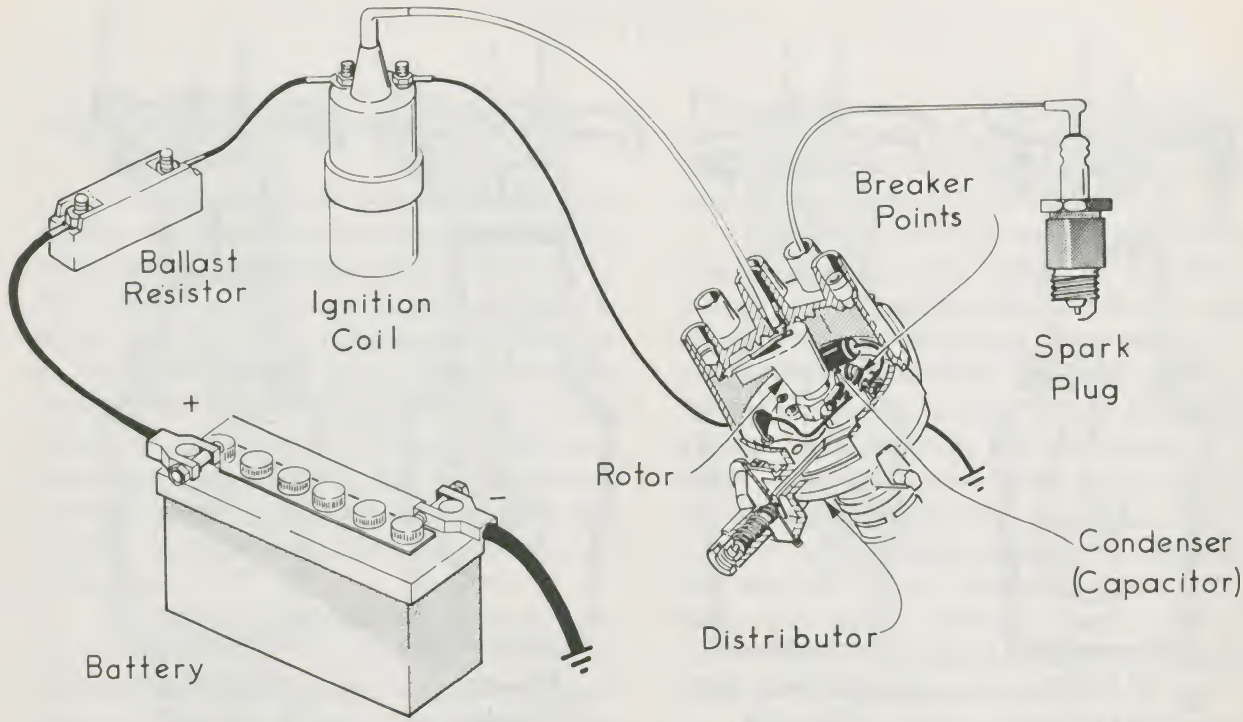
Breaker
Points
Ballast
Resistor
Ignition
Coil
Spark
Plug
+
Rotor
−
Condenser
(Capacitor)
Distributor
Battery

Figure 6.

EXPERIMENT A-1. The Ignition System

The purpose of this experiment is for you to familiarize yourself with the principal components of the ignition system of an automobile. First you should examine the system and identify the following components. Figure 6 will be very helpful for doing this.

Battery (12 V). Note that the red lead is connected to the positive terminal of the battery.

Ignition Switch. The part of the ignition switch we are concerned with is simply an "ON" and "OFF" switch which connects the battery to the circuit.

Ballast Resistor. The ballast resistor is inside a white block of ceramic insulating material. Its location in the circuit is between the battery and the positive terminal of the ignition coil.

Ignition Coil. The ignition coil is in an iron case. The coil has three terminals. The central terminal provides high voltage to the central terminal of the distributor. The terminal marked "+" is connected (through the ballast resistor) to the positive terminal of the battery. The remaining terminal, marked "–," is connected to the breaker arm in the distributor.

Distributor. The distributor is made up of several subassemblies:

The *distributor cap* is usually made of bakelite, a good electrical insulator. It fits snugly over the distributor housing, and is held on by two clips. The cap contains the spark plug cable towers arranged evenly around the outer edge, as well as a cable tower located in the center of the cap to receive the high voltage connecting wire from the ignition coil.

The *rotor* fits above the cam and rotates with the shaft.

The *cam* is a six (6-cylinder engine) or an eight (8-cylinder engine) sided wheel to which the rotor is attached.

The *breaker arm* rubs against the cam to open and close the *breaker points.* One of the breaker points is stationary and the other is on the breaker-arm assembly. Opening and closing of these points interrupts the current in the circuit.

The *capacitor* is contained in a metal cylinder which is grounded* to the chassis of the car, and forms one terminal of the capacitor. A black wire connects the other terminal of the capacitor to the breaker arm and points. Its purpose is to reduce unwanted current flow (*arcings*) across the opened breaker points.

Spark Plug. The spark plug has a central conductor which projects into the engine cylinder. The high voltage generated by the ignition coil causes a spark to jump between this central conductor and a conductor which is welded to the base of the plug and is grounded to the chassis. This spark ignites the air-fuel mixture.

In the laboratory set-up, an electric motor or variable speed electric motor or variable speed electric drill is used to rotate the distributor shaft. In the automobile engine, a set of gears rotates the distributor shaft once for each two revolutions of the motor. In this way, each cylinder is caused to fire every other time its piston rises.

Take the work sheet for this experiment from the back of the module to answer the following.

1. *With the battery switch off,* carefully remove the distributor cap. Move it out of the way and identify the breaker-arm assembly, breaker points, cam, rotor, and capacitor.

*In an automobile electrical system, "grounded" means attached to the metal chassis, which then becomes part of the circuit.

With the battery switch still off, rotate the distributor shaft by hand and observe the movement of the rotor. Look at the terminals inside the distributor cap.

How might the position of the rotor with respect to the distributor cap terminals be used to route the spark to each of the spark plugs at the proper time?

2. Again, with the switch off, rotate the distributor shaft by hand. Observe the action of the breaker points.

   How many times do the points open and close for each revolution of the distributor shaft?

3. Remove the connecting wire from the top of the ignition coil. Remove one of the spark plug wires from the distributor cap and plug it into the top of the ignition coil. Place the capacitor switch in the "in" position and turn the battery switch on.

   CAUTION: There is now high voltage present. Be careful not to come in contact with the spark plug or any of the exposed parts in the distributor, or you may get a nasty shock.

   Does the spark at the spark plug occur as the points open or as they close?

4. Watch the points as you rotate the distributor shaft.

   Does a spark also occur at the points?

5. Place the capacitor switch in the "out" position and rotate the distributor shaft.

   What difference does this make in the spark at the plug and that at the points?

6. Turn off the battery switch. Return the wires to their original positions: the center distributor wire to the ignition coil; and the spark plug wire to its outer distributor tower. Replace the cap on the distributor, being sure that the key on the bottom of the cap is seated in the keyway in the base. Lock the cap in place by pressing the spring clips into place on the cap. Set the capacitor switch to "in" and turn on the battery switch. Rotate the distributor shaft by hand. Observe the routing of the spark to the terminals inside the distributor by the rotor tip.

   What is the mechanism which causes this circular progression of the spark around the distributor terminals to be routed so that the cylinders fire in a specified order (e.g., 1-8-4-3-6-5-7-2), with each plug firing on every other revolution of the motor?

7. Now that you have observed this action in slow motion, turn on the drive motor and the battery switch. Observe the sparking with the distributor turning at a low and then a high speed.

   Can you detect any difference in the spark at the spark plugs as you change the speed at which the distributor shaft is turning?

THE COIL

You can watch the mechanical distributor parts in action, but there is nothing obvious to observe to help to understand the coil. With a bit more knowledge, you can use electrical measurements to find out how the coil operates. For now, you only need to know that it contains two coils of wire. One is called the *primary* and the other is called the *secondary*. A sudden interruption of electric current in the primary coil produces a very high voltage in the secondary coil. This phenomenon results from *electromagnetic induction.*

ELECTROMAGNETIC INDUCTION

The automobile ignition system must produce the thousands of volts necessary to cause a spark to jump across the spark plug gap although only 6 or 12 V is available at the battery. This voltage increase is produced by the ignition coil. The current in the primary coil of wire is interrupted by the opening of the breaker points. When this interruption occurs, a large voltage is created in the secondary windings. This effect is called *electromagnetic induction.* To understand electromagnetic induction, you must first understand some relations between magnetism and electricity.

Early in the nineteenth century, scientists discovered that an electric current can exert a force on a small nearby magnet. This showed that an electric current produces magnetism. Modern science regards all magnetic effects as resulting from electric currents. Even permanent magnets derive their magnetism from electric charges which move in atoms in the material.

To investigate magnetism and the magnetic effects of electric currents, do Experiment A-2.

EXPERIMENT A-2. Magnets and Electromagnets

Part I. Magnetism

The operation of the ignition system depends strongly on certain principles and laws of *electromagnetism.* To understand those principles and laws, one must first understand the behavior of simple magnets. Some magnets, nails, tacks, paper clips and other items have been provided.

1. Run a paper clip, tack, or nail along a magnet from end to end. Where is the attraction the strongest?

2. What happens near the middle of the magnet?

3. What happens when different parts of the magnet are brought near a pile of small nails or tacks?

4. You have been provided with a long, narrow bar magnet. Repeat steps 1, 2, and 3 with this magnet. Now break this magnet into two pieces of about equal length and repeat steps 1, 2, and 3 with each of these pieces. What do you observe?

5. Suspend one of the rod magnets on a string so that it swings freely in a horizontal plane as shown in Figure 7. Bring another magnet near the suspended one. Explore how the ends, or *poles,* of the two magnets interact. You may have heard that "like poles repel; unlike poles attract each other." What is "alike" about the poles that repel each other? Is it some tangible, visible "likeness"?

6. Examine what is actually meant by the terms "like" and "unlike." Return to the suspended rod magnet (as in Figure 7). Observe how it settles down after it has received a "kick," or deflection. Watch it very carefully; keep track of where each pole ends up regardless of the orientation from which you start the magnet. What do you observe?

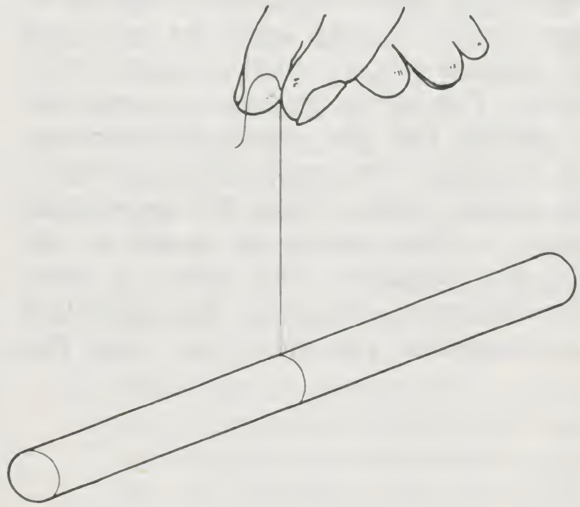

Figure 7.

You can make a magnetic compass by suspending a magnet from a thread. With colored chalk or a piece of tape, mark the pole that always ends up pointing toward the north; we will call this "north seeking" or simply the *north pole* (N-pole) of our magnet. The other end is the *south pole* (S-pole).

Perform the same experiment with a second magnet. (Be sure to remove the first one of them to a distance such that it does not influence the second one.) Mark the pole that always ends up toward the north. You now have a simple, meaningful sense in which poles are "alike" or "unlike." Now let us investigate how like and unlike poles interact.

7. Keeping one magnet suspended, as in the preceding experiment, hold a second magnet several inches below the suspended one, as shown in Figure 8. How does the suspended magnet behave as the second magnet is turned around so that it points in different directions in the horizontal plane?

Watch how a compass needle behaves as you place a bar magnet near it in various positions. (Do not bring the magnet too close, because you might damage the compass.) Explain the behavior of the compass in terms of the ideas you have established so far.

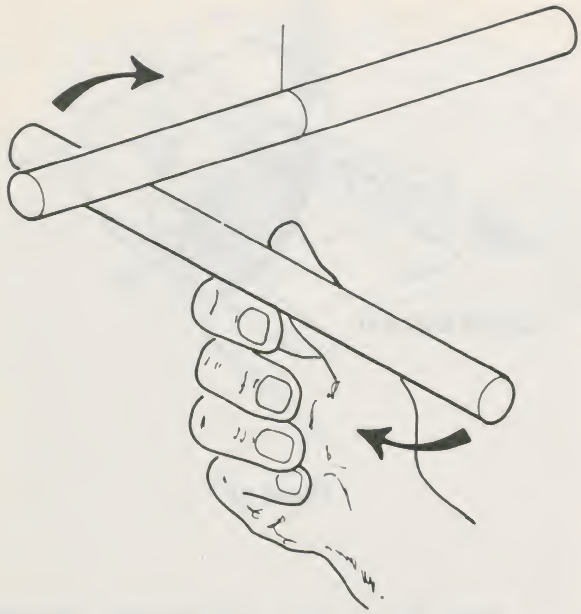

Figure 8.

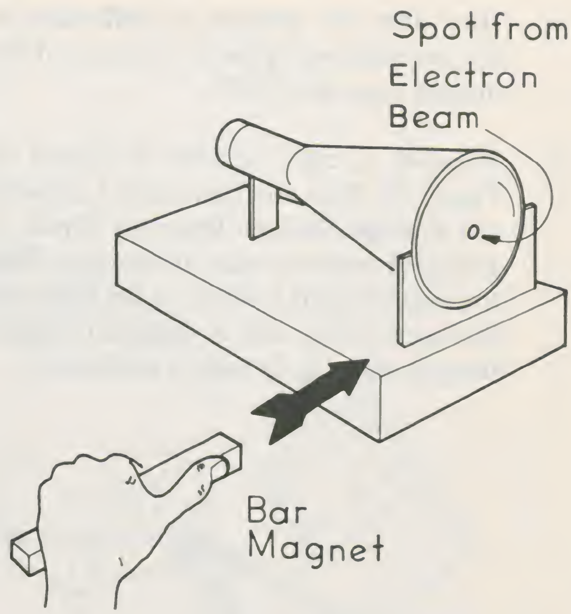

Figure 9.

8. What do all of your observations up to this point suggest about the earth, as far as magnetic behavior is concerned?

9. Take a third magnet. Use it as a reference device. How do the poles of the first two magnets interact with the third magnet? Using your known magnets, can you identify the N-pole and S-pole of the third magnet? Does the whole scheme of "like" and "unlike" poles hang together consistently?

10. Take the small compass which has been provided and move it around a bar magnet lying on the table. How does the compass point when placed beside the middle of the magnet? How does the compass point when moved farther and farther away from the magnet on a line which is perpendicular to it?

11. Place a bar magnet under a clear plastic or glass sheet. Sprinkle iron filings on the sheet and gently tap it. Note how the filings arrange themselves, and sketch the resulting pattern. Where do lines formed by the filings tend to be closest together? Is the pattern symmetric in any way?

12. Disturb the pattern several times, then rearrange it by tapping the sheet. After each tapping, do the filings arrange themselves in essentially the same pattern?

13. Do you see any relation between the pattern of iron filings and the direction of the compass needle at various points?

Part II. Electromagnetism

1. Do magnets exert forces on electric charges? To answer this question, do the following demonstration. Turn on a cathode-ray tube or an oscilloscope and obtain a spot on the screen. This spot is due to a beam of electrons moving through the tube. The electrons strike the sensitive screen and cause it to give off visible light at the impact point. Bring the N-pole of a magnet near the cathode-ray tube (CRT) from one side of the spot, as shown in Figure 9. What happens to the spot on the screen?

2. Turn the magnet around and bring the S-pole near the CRT from the same side of the spot. What happens to the spot on the screen?

3. How does the amount of deflection of the spot depend upon the distance of the magnet from the CRT?

4. Suspend a coil of wire as shown in Figure 10. Pass a current of 1.5 amperes (A) through the coil. Bring the N-pole of a magnet near the axis of the coil. Does the magnet exert a force on the coil? Try the same thing with a different current through the coil. Is there a difference?

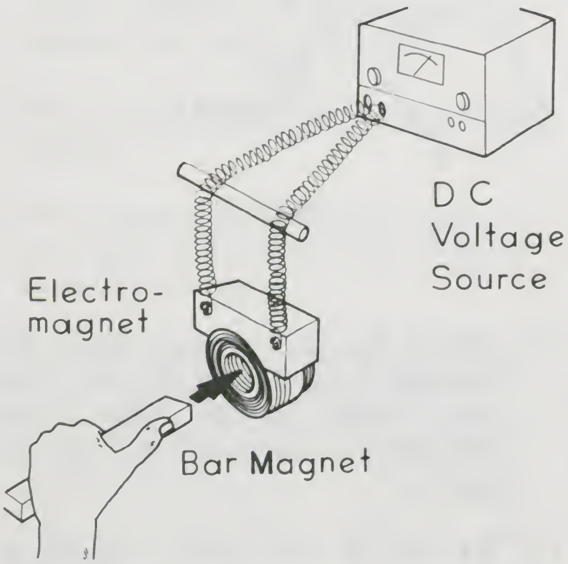

Figure 10.

5. Using the small compass, determine whether or not the coil has north and south poles. Reverse the direction of current by interchanging the leads at the power supply. What happens to the poles of the magnet produced by the current-carrying coil?

6. Insert a cardboard sheet through the center of the coil as shown in Figure 11. Adjust the current again to about 1.5 A. Sprinkle iron filings over the sheet. Tap the sheet, and sketch the pattern produced.

7. How does the pattern compare to that produced by the bar magnet?

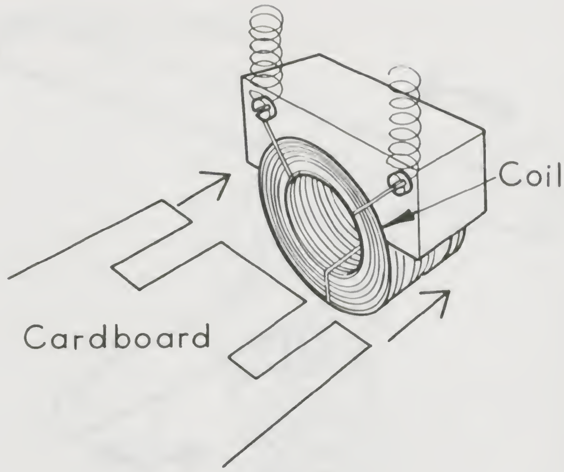

Figure 11.

Thus far we have investigated magnetic fields which are constant and are the result of constant currents. What happens when the current changes or the magnets move? Let us investigate these questions.

8. The arrangement for this investigation is shown in Figure 12. The *galvanometer* is a device which indicates an electric current and the direction of that current. Place the bar magnet inside the coil. When the magnet is stationary, what is the current reading through the galvanometer?

9. Suddenly remove the magnet from the core of the coil. Does the galvanometer deflect? In what direction?

10. Suddenly move the magnet back into the coil. Does the galvanometer deflect? In what direction?

11. Turn the magnet around, end for end, and again suddenly move it into the coil. What is the direction of deflection now? What is the direction of deflection when it is removed?

12. Repeat the above steps at different speeds. How does the maximum deflection depend on how fast you move the magnet?

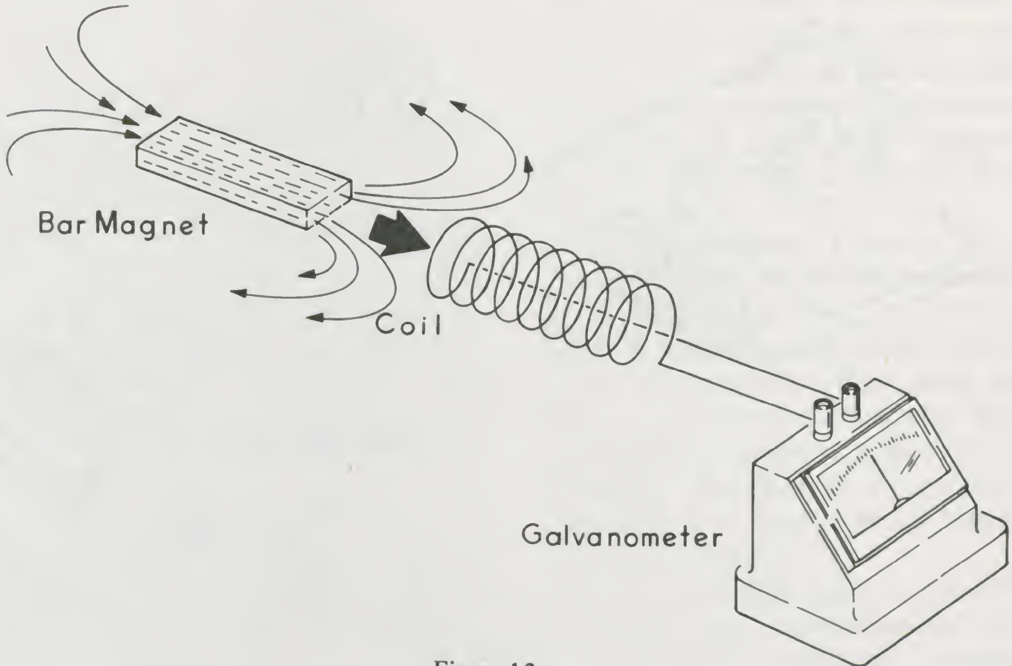

Figure 12.

13. Keep the magnet stationary and move the coil rapidly toward the magnet. Now move the coil away. How does this situation compare with when the magnet is moved?

14. Hold the coil so that one of the open ends is near the end of the magnet. Without changing the distance from the coil to the magnet, rapidly rotate the coil so that the other open end faces the magnet. Do you observe a deflection of the galvanometer? Which way? Turn the coil the other way. What do you observe?

15. Connect the square coil to the galvanometer and adjust it to make the end as nearly square as possible. Hold the open end of the coil near the end of the magnet. Without changing the distance from the coil to the magnet, suddenly collapse the coil by pressing on the opposite edges. What do you observe on the galvanometer? Try this in reverse.

16. Since we have observed that the magnetic fields produced by bar magnets and those produced by bar magnets and those produced by a coil of wire have the same basic characteristics, we should be able to use a second coil carrying a current as a "magnet" to produce the effects observed in steps 8-13. Furthermore, the strength of the "magnet" made with a coil depends on the current so the strength of this magnet can be changed by increasing or decreasing the current through the coil.

    Place two coils so that their axes are in a line and the coils are as close together as possible, as shown in Figure 13. Turn on the switch to produce a current in coil 1. What happens to the galvanometer connected to coil 2?

17. Now turn off the switch, which stops the current in coil 1. What happens to the galvanometer now?

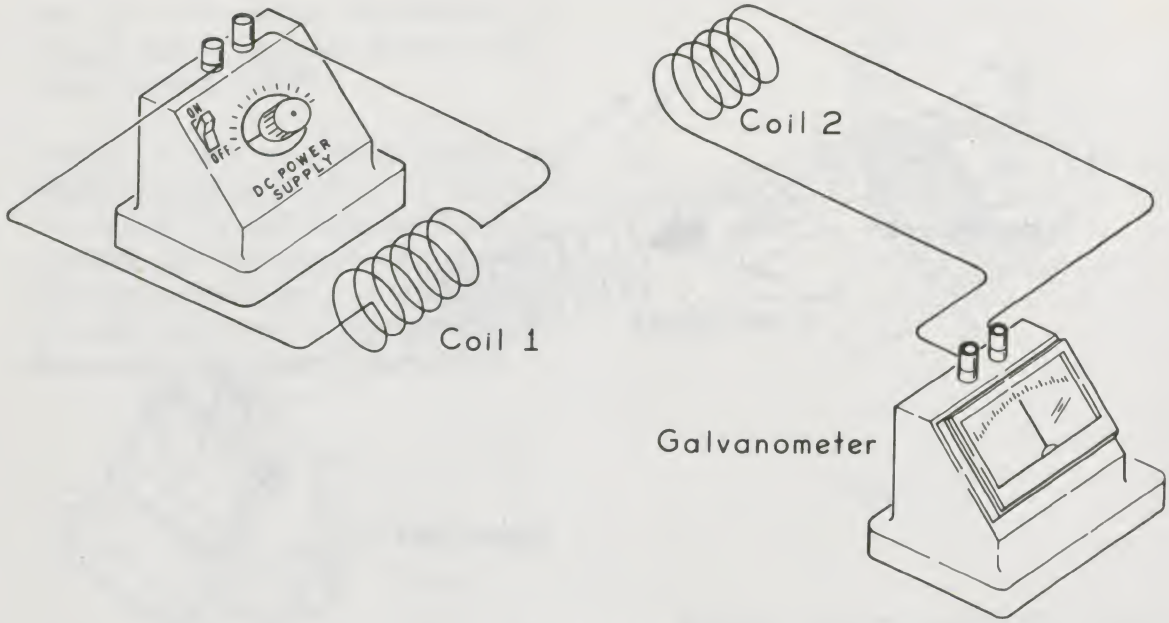

Figure 13.

18. Turn coil 2 over so that the end originally farthest from coil 1 is now closest. Repeat steps 16 and 17. How does the direction of the galvanometer needle deflection compare with that seen in steps 16 and 17?

19. How does the interaction of these two coils change when the coils surround a substance other than air? To examine this situation, place each of the coils over the ends of the iron core provided. Turn the current on and off in coil 1 and record the maximum deflection developed.

20. How does this maximum deflection compare with what was observed in step 16?

SOME OBSERVATIONS ABOUT MAGNETISM

In Experiment A-2, you learned to describe the end of a bar magnet as a magnetic "pole." You then studied the interaction of the two types of poles to arrive at the principle that like poles repel and unlike poles attract. By using a compass you probed the region surrounding a magnet. As the compass was moved farther and farther away from the magnet, the effect on the compass got weaker and weaker, until the relatively weak effect of the earth's magnetism took over.

Question 2. Suppose that you are given two iron bars, which are identical in appearance, and told that one is a magnet and the other is not. How could you tell which is the magnet, using absolutely no other object? (Hint: For the one which is a magnet, where are the poles located?)

Question 3. What is the direction of magnetic deflection for the electron shown in Figure 14?

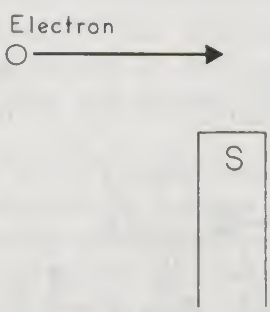

Figure 14.

MAGNETIC FIELDS

Forces act between two magnetic poles which do not touch each other, and you may have wondered how one magnet "knows" that the other magnet is there. That is, how is the force transmitted between the magnets? One way to visualize the process is that the presence of a magnet somehow changes the space surrounding it, so that any other magnetic material brought into that region of space experiences a *force.* The "change in space" brought about by a magnet is called its *magnetic field.*

A small magnet, such as the compass, can be used to reveal the presence of such a field. A compass thus reveals the magnetic field of the earth, even though the entire field cannot be surveyed. (The earth is an enormous magnet, and its magnetic field extends over regions much larger than the earth itself. Similarly, the field of a bar magnet can be observed over regions much larger than the bar magnet itself.)

We arbitrarily agree to call the direction in which the "north-seeking" pole of a compass needle points the "direction of the magnetic field" at that point.

MAGNETIC FIELD LINES

A magnetic field is invisible, but it can be envisioned as a set of curved *magnetic field lines,* as shown in Figure 15. Such lines can be constructed by using a compass. Move the compass from point to point in the region of the magnet. Draw a small arrow at each position to show the direction in which the north end of the compass points at that position. Each such arrow will be tangent to a magnetic field line through that point.

Remember, the lines do not actually exist. They are used to aid understanding of magnetism. When using these field lines to picture a magnetic field, the direction of the magnetism at any point in the field is indicated by the direction of the lines at that point. The strength of the magnetic field is indicated by the number of lines crossing a unit area. In other words, the closer together the lines are, the stronger the magnetic field.

Current in a conductor can be maintained only by an electromotive force (EMF) across the ends of the conductor. A coil in which a current is induced by a changing magnetic field must therefore have an EMF within it. Such an EMF is called an *induced*

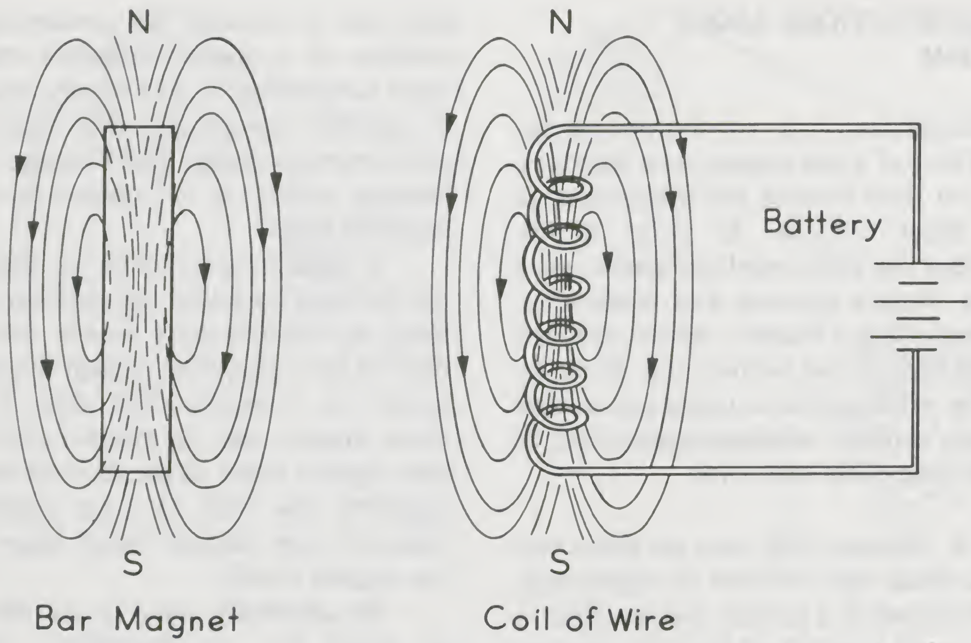

Figure 15.

EMF. The principle that a change in the magnetic field surrounding a conductor induces an EMF within the conductor is called *Faraday's Law.* We shall see the relation of Faraday's Law to the ignition system in what follows.

Question 4. If a magnet and a nearby coil are moved together with the same velocity, will there be an EMF induced in the coil? Explain why or why not.

THE IGNITION COIL

Suppose that we wish to cause sparks to jump across air gaps, such as the gap between the electrodes in an automobile spark plug. Such sparks require a high voltage, roughly 15,000 V, for a normal spark plug. This high voltage is necessary to overcome the high resistance of air to charge flow.

As you have seen, when the two coils are placed close to each other, any increase or decrease in current through one coil will induce an EMF (or "voltage") in the second coil. This is the basic principle of operation of an auto ignition coil. Devices which utilize this principle of transforming electric energy from one coil of wire to another by means of changing magnetic fields are called *transformers.* An ignition coil which is a specialized kind of transformer is shown in Figure 16.

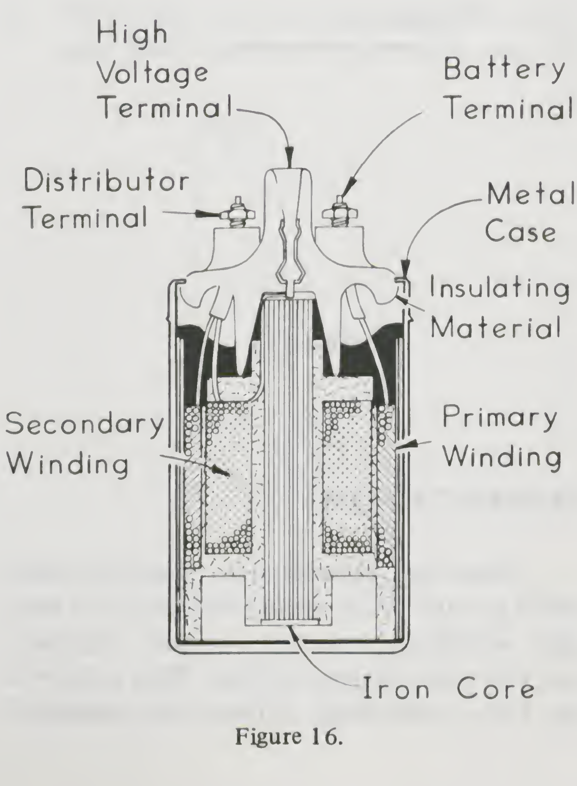

Figure 16.

If you were to take apart an ignition coil, you would find a "primary" winding (coil) and a "secondary" winding, arranged around an iron core. There is a very large number of turns in the secondary compared to the small number in the primary. The primary coil winding is made of a few hundred (150 to 250) turns of 20-gauge wire, which is about the size used in making ordinary paper clips. The secondary coil winding consists of many thousands of turns (15,000 to 25,000) of 40-gauge wire, which is about the same diameter as human hair.

The soft iron core concentrates the magnetic field lines through the coils to improve the efficiency of the arrangement. The core is made of thin strips, or *laminations,* and the surface of each strip is coated with a very thin insulating film of varnish or oxidized iron.

MAGNETIC FLUX

As shown in Figure 15, the lines are closer together at the ends of the magnets than they are at any other place around the magnet. This means that the magnetic field is strongest at the poles of a bar magnet. Magnetic field lines are continuous, closing on themselves with no beginning or end. With a coil (electromagnet), the lines loop through the center of the coil of wire; whereas, in a bar magnet, they pass through the inside of the magnet.

When a piece of iron is inserted through the center of a coil, it increases the strength of the magnetism in that region, as if the field lines crowd together to go through the metal. The total number of magnetic field lines in a region of space is called the *magnetic flux.* The more magnetic field lines crossing a given area, the greater the magnetic flux, and the greater the strength of the magnetism in that area.

WHAT HAS MAGNETISM TO DO WITH THE IGNITION SYSTEM?

In Part II of Experiment A-2, the effect of a magnetic field on moving electric charges (electric current) was illustrated. You also found that a coil of wire has the same magnetic properties as a permanent magnet. Such coils are called *electromagnets.* You then observed that a magnet (or an electromagnet) which was passed into or near another coil produces a current in that coil.

The polarity of the magnet or electromagnet and the direction of motion determine the direction of current in the second coil, and the faster the motion, the greater the current. Moving a magnet into a coil changes the magnetic field surrounding the wire in that coil. You observed that you could produce an electric current in a stationary coil by placing it near an electromagnet which is turned on and off. Turning the electromagnet on or off increases or decreases the magnetic field surrounding the coil. Thus, a changing magnetic field is produced without moving either coil. You saw that even if the magnetic field remained unchanged, a current can be produced in the coil by changing its area.

An electric current produced in any of the above-described ways is said to be an induced current.

Finally, you found that the effect of the changing magnetic field produced by a coil can be greatly increased by placing an iron core in the coil.

THE PRIMARY CIRCUIT

Figure 17 shows the primary circuit, which is complete only when the breaker points are closed. The 12-V battery supplies a current which reaches a maximum of about 3 A through the primary of the coil, since the resistance of the primary circuit is about 4 ohms (Ω). This current is the source of the magnetic field in the primary coil. Notice that the circuit is completed through the metal parts of the engine and chassis, which act as a common "ground."

The Secondary Circuit

Once the points have opened, the magnetic field built up in the coil by the current in the primary circuit suddenly decreases to zero

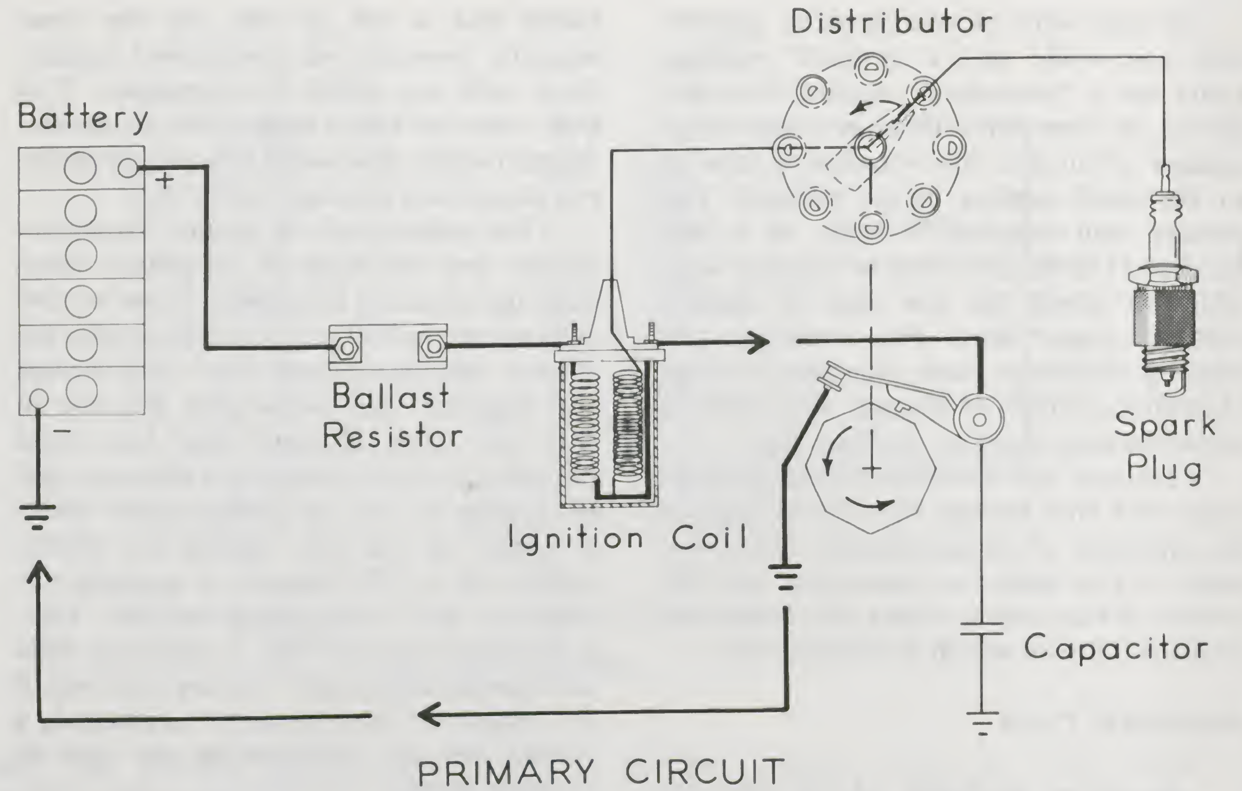

Figure 17.

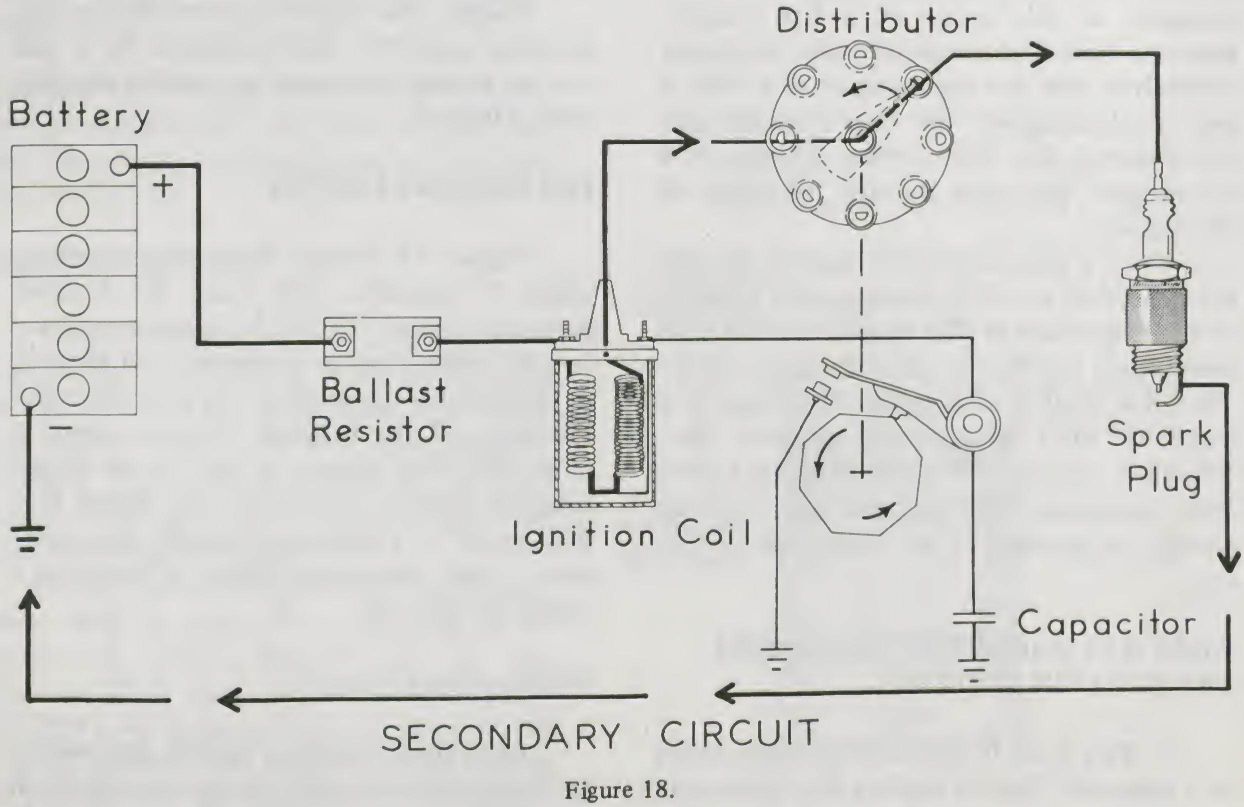

Figure 18.

(collapses), as the current falls rapidly to zero. This collapsing field then *induces* the high voltage in the second coil and the high voltage passes through the rotor cap producing a spark at the plug. As indicated in Figure 18, the path of the secondary current is through the primary coil, the ballast resistor, and the battery, to ground. However, the current in the secondary is so small that it has little effect on the battery. As in the primary circuit, the metal engine provides the "ground" which completes the circuit in the secondary.

Inducing High Voltages

When the magnetic flux produced by the primary coil changes quickly, as it does when the points open, an EMF is induced in *each* turn of the secondary coil and these EMFs add up, so that when the secondary has a large number of turns compared to the primary, the induced secondary voltage can be very large.

Polarity of the Secondary Coil

Many physical principles apply to the automobile ignition system, but we shall not have time to examine them all in detail in this module. One factor that should be noted is the *polarity* of the secondary coil. In Experiment A-2, you noted that the direction of the induced current depends on the relative orientation of the two coils. The secondary coil is wound so that the induced secondary voltage is negative rather than positive. The center electrode of the spark plug is at lower potential than the outer grounded electrode. The center electrode of a spark plug gets much hotter than the grounded electrode. A hot electrode gives up electrons more easily than does a cold electrode. For this reason the voltage needed to cause sparking across the electrodes is 20 percent to 40 percent lower than if the center electrode were positive and electrons had to go the other way. In Figure 18, the arrows indicate the direction of electron flow in the secondary circuit.

EDDY CURRENTS

The iron core of the ignition coil is *laminated* to reduce energy losses. Iron is a fair conductor of current, and, in a changing magnetic field, currents are induced in it. These induced currents are called *eddy currents* because the current paths are small circles, similar to eddies in a stream. Eddy currents produce heat. The energy in this heat comes from the electrical energy input to the coil. By laminating the core, the current paths are broken up, and energy losses in the core are reduced.

TIMING ADVANCE

Timing advance, the degree to which sparking occurs before the piston reaches top dead center, is regulated by two mechanisms in the distributor. One of these is the *centrifugal advance mechanism.* In this mechanism, two spring-mounted weights on the distributor shaft move outward at higher engine speeds. A mechanical linkage uses this outward motion of the weights to rotate the cam assembly relative to the distributor shaft. This "forward" rotation causes the cam to open and close the breaker points earlier in the engine cycle.

The second mechanism is the *vacuum advance.* When the engine is idling, the density of the air-fuel mixture in the cylinders is lower than at higher engine speeds. This lower density slows the rate at which fuel burns in the cylinders. Therefore, the spark must occur earlier in the cycle to allow the completion of burning at the most favorable piston position. The vacuum advance consists of a diaphragm which is flexed by the difference in pressure between the outside air and the gases in the *intake manifold.** As it flexes, it turns parts

* The intake manifold is the part of the engine through which the fuel mixture travels from the carburetor to the various cylinders of the engine. Although the pressure inside the intake manifold depends on how the engine is operating, it is usually lower than atmospheric pressure.

of the distributor in a manner which advances or retards the spark. By advancing the spark better performance over the full range of engine speeds is achieved. For pollution control, spark advance is adjusted to both engine speed and air temperature.

Question 5. Describe in your own words the function of the battery in an ignition system.

SUMMARY

The Ignition System

The *ignition system* of an automobile provides the properly timed ignition of the air-fuel mixture in the internal combustion engine. It consists of five basic parts along with the necessary electric wire to connect them. The five parts are: the *battery,* the *ignition coil,* the *distributor,* the *spark plugs,* and the *ballast resistor.*

The *ignition coil* is a high-voltage transformer which contains a primary and secondary coil wound coaxially around a laminated core of soft iron. (The secondary winding is wound around the core and the primary winding is wound around the secondary.) The ignition coil transforms the low primary voltage into the high secondary voltage required to produce a spark in the spark plug.

The *distributor* is a mechanical device used to distribute the high voltage from the secondary winding of the ignition coil to each spark plug at precisely the right time for proper combustion in that cylinder. The distributor contains several parts: the *distributor cap,* the *rotor,* the *breaker points,* and the *terminal.*

The *rotor* rotates inside the distributor cap at one-half engine speed and directs the secondary high voltage to each spark plug in turn.

The *breaker points* form a timed mechanical switch that interrupts the current in the primary circuit.

The *capacitor* is connected across the breaker points to reduce arcing across them when they open.

The *spark plug* is a device with two metal terminals with a small gap between them, so that when the proper high voltage is applied, an electric spark jumps from one terminal to the other.

The *ballast resistor* is a wire-wound, ceramic-coated resistor, whose resistance increases with temperature to ensure a more uniform spark at all engine speeds.

The *ground* is the term used for the return path necessary to complete the primary and secondary electric circuits. The metal parts of the motor and chassis make up this part of the circuits.

Spark advance is the firing of the spark plug before the piston has reached top dead center on the compression stroke.

Physics Related to the Ignition System

The *pole* of a magnet is that area of the magnet where magnetic forces appear to be the strongest. There are two different kinds of poles [referred to as north (N-pole) and south (S-pole)], which for rod or bar magnets are located at the ends.

Unlike poles of magnets attract each other, and *like poles* repel each other.

Magnetic flux is the total number of magnetic field lines in a given area. The number of lines of flux per unit area indicates the strength of magnetism in that area.

An *electromagnet* is a current-carrying coil of wire which behaves just like a permanent magnet as long as a steady current flows in the coil.

Electromotive force (EMF) is the term given to that property of a *source* of electricity which can cause a current to flow through a resistance. It is measured in volts.

An *induced EMF* is the EMF produced by a changing magnetic field.

Faraday's Law is the principle which governs an induced EMF: A changing magnetic field surrounding a conductor induces an EMF within the conductor.

Eddy currents are induced in metal parts (such as iron cores) by changing magnetic fields. They may result in substantial energy losses.

GOALS FOR SECTION B

The following goals state what you should be able to do after you have completed this section of the module. The example which follows each goal is a test item which fits the goal. Answers to the items immediately follow these goals.

1. *Goal:* Know the definition of *time constant.*

   Item: The scope trace in Figure 19 shows the voltage across a ballast resistor of an ignition system as the points open and close with the capacitor and secondary circuit disconnected. What is the time constant of the circuit?

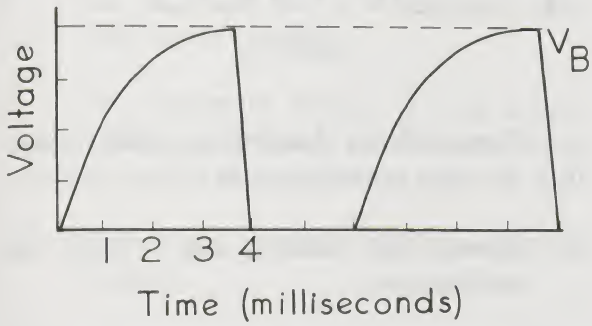

Figure 19.

2. *Goal:* Know how to calculate magnetic field from the force it produces on a current-carrying wire.

   Item: A wire 2 m long and carrying a current of 10 A is subjected to a force of 10^{-3} N when oriented along an east-west axis, due to the earth's magnetism. What is the earth's magnetic field at that position?

3. *Goal:* Know the electromagnetic terms defined in this section of the module: *magnetic flux, self-inductance, mutual inductance,* and *capacitance.*

   Item: A square, flat coil 10 cm on a side with 10 turns is positioned at right angles to a magnetic field of 3 T. What is the magnetic flux through the coil?

4. *Goal:* Understand Faraday's Law as expressed in terms of changes of magnetic flux.

   Item: The coil described in Item 3 is rotated 90° about a vertical axis in 0.55 second. What EMF is induced in the coil?

5. *Goal:* Understand the combination of Faraday's Law and Lenz's Law when it is expressed in terms of electric current.

   Item: At a particular time after the points have closed, the current in the primary circuit of an ignition system has reached 2.0 A. During the next 0.1 ms the current increases by 0.1 A. If the primary coil has an inductance of 7 mH, what is the value of the self-induced EMF, and what is the net voltage appearing across the coil? Assume the battery voltage is 12 V.

Answers to Items Accompanying Previous Goals

1. About 1 ms
2. 5×10^{-5} T
3. 3×10^{-5} Wb
4. 0.6 V
5. −7 V;
   Net voltage = 12 V − 7 V = 5 V

ELECTRICAL COMPONENTS

In Section A you studied the general features of the automobile ignition system. To understand the details of its operation, you must learn how each of its components contributes to the electrical properties of the whole system. To study these components, you should now do the following experiment.

EXPERIMENT B-1. Electrical Characteristics of Ignition System Components

CAUTION: High voltages are present in this experiment. Be careful not to touch the high voltage connections when the ignition switch is on.

In Experiment A-1, you observed the mechanical operation of the ignition system and identified the components by their physical appearances. The purpose of this experiment is to determine the effects these components have in an electric circuit. To do this you will use an oscilloscope to make measurements in the circuit. If you are not familiar with the use of the oscilloscope, work through the appendix before starting this experiment.

Disconnect the ignition coil from the primary circuit and connect a *second* ballast resistor in its place. Place the capacitor switch in the "out" position. The primary circuit then corresponds to the diagram shown in Figure 20.

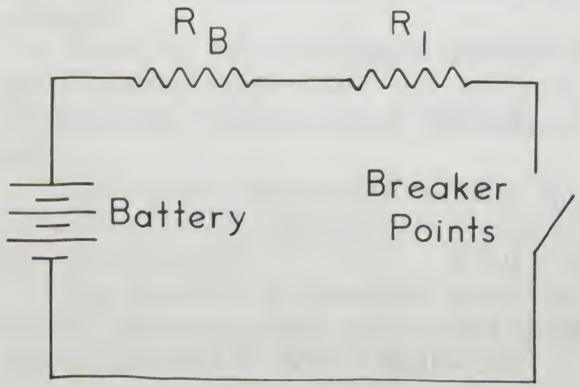

Figure 20.

Connect the vertical input of the oscilloscope across the first ballast resistor R_B. Turn on the drive motor and the ignition switch. Set the motor control to a slow speed. Adjust the time base controls of the oscilloscope to obtain a steady trace showing two complete repetitions of the trace, or *cycles,* as shown in Figure 21. If the trace appears upside down, it may be necessary to reverse the oscilloscope leads.

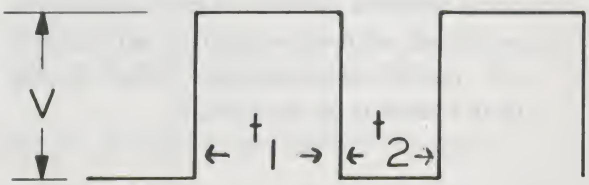

Figure 21.

The points are closed during time t_1, and they are open during the time t_2.

1. Measure the times t_1 and t_2 with the oscilloscope.

2. Measure the voltage V with the oscilloscope.

Turn off the ignition switch and the drive motor. Disconnect R_B from the circuit.

3. Use an ohmmeter to measure the resistance R_B.

4. Use Ohm's Law to calculate the current (I) through R_B when the points are closed.

Reconnect the ballast resistor and the ignition coil but disconnect the high voltage lead from the center of the ignition coil. The primary circuit should now correspond to the diagram in Figure 22.

Again connect the oscilloscope vertical input across the ballast resistor. Set the drive motor to run at a slow speed and turn on the ignition switch. Adjust the oscilloscope to show two complete cycles.

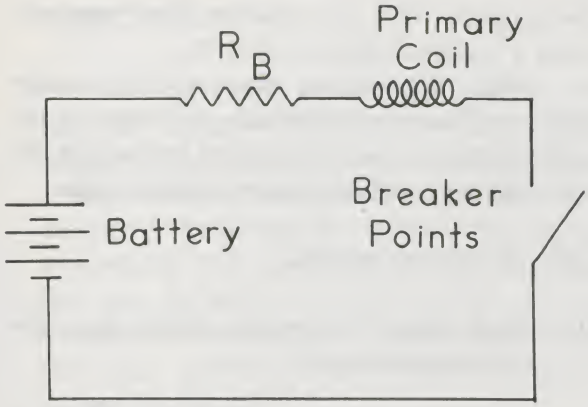

Figure 22.

5. Sketch this trace.

6. What is the major difference between this trace and that seen with only resistance in the circuit?

The maximum voltage on the oscilloscope trace corresponds to the maximum current through the resistor.

7. What is the maximum voltage across the resistor?

8. Calculate the maximum current through the resistor.

9. Measure the time required for the voltage across the resistor to go from zero to about 63 percent of its maximum value. This time, called the *time constant,* can be used to characterize the time behavior of the circuit. It will be explained later.

Turn off the drive motor and the ignition switch. Disconnect the ignition coil and replace it with a 10,000-Ω resistor. Turn the capacitor switch to "in." The primary circuit now corresponds to the diagram in Figure 23.

Connect the vertical input of the oscilloscope across the 10,000-Ω resistor. Set the drive motor to run at slow speed and turn on the ignition switch. Adjust the oscilloscope to show two complete cycles.

10. Sketch the pattern shown on the oscilloscope.

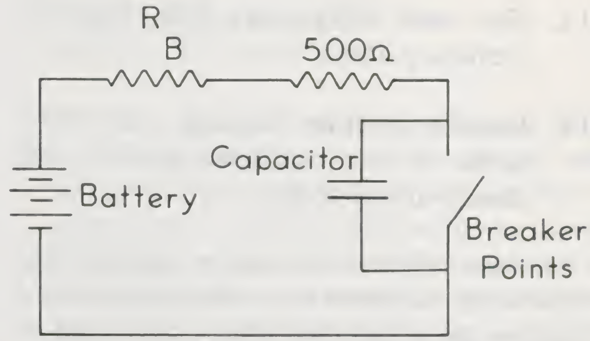

Figure 23.

11. How does this trace differ from the previous traces?

12. Measure the time required for the voltage across the resistor to drop about 37 percent of its maximum value. (Go 63 percent of the way from maximum to zero.) This time is also called the time constant.

Turn off the drive motor and the ignition switch. Remove the 10,000-Ω resistor from the circuit and reconnect the ignition coil, but do not connect the high voltage lead. With the capacitor "in," the circuit should correspond to the diagram shown in Figure 24.

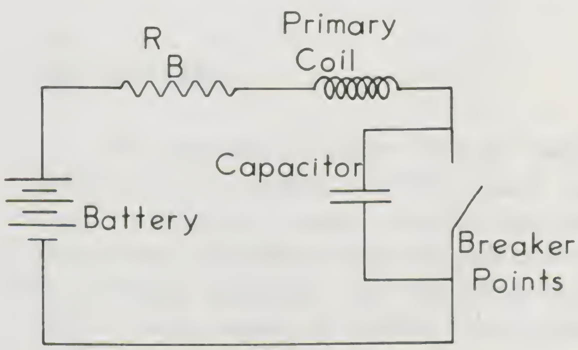

Figure 24.

Connect the vertical input of the oscilloscope across the ballast resistor. Set the drive motor to run at slow speed and turn on the ignition switch. Adjust the oscilloscope to show two complete cycles.

13. Sketch the 'scope pattern.

14. How does this pattern differ from the previous patterns?

15. Measure the time between consecutive peaks of the oscillation pattern (the closely spaced peaks).

Turn off the drive motor and the ignition switch. Connect the vertical input of the oscilloscope across the primary coil. Turn on the drive motor and the ignition switch. Adjust the oscilloscope to obtain two complete cycles.

16. Sketch the pattern.

17. Measure the time between two successive oscillation patterns.

Turn off the drive motor and ignition switch. Connect the high voltage lead from the ignition coil to the center terminal of the distributor and make certain all connections between the distributor and the spark plugs are correct. With the capacitor "in," you now have a complete ignition system.

With the vertical input of the oscilloscope still across the primary coil, turn on the drive motor and ignition switch and adjust the oscilloscope to obtain two complete cycles.

18. Sketch the pattern.

19. How does this pattern differ from the previous pattern?

Turn off the ignition switch and drive motor. Connect the oscilloscope vertical input to the ballast resistor. Turn on the drive motor and ignition switch and obtain two cycles.

20. Sketch the pattern.

21. How does this pattern differ from that across the ballast resistor when the high voltage lead was disconnected?

INDUCTANCE

In Experiment B-1, as the points open to stop the current and then close to allow charge to flow again, several interesting properties of the components could be seen. Many properties would not be evident if the current were steady and uninterrupted. For example, the coil, in series with the ballast resistor, changed the form of the 'scope pattern from that seen with the resistor alone. Figure 25 shows this change.

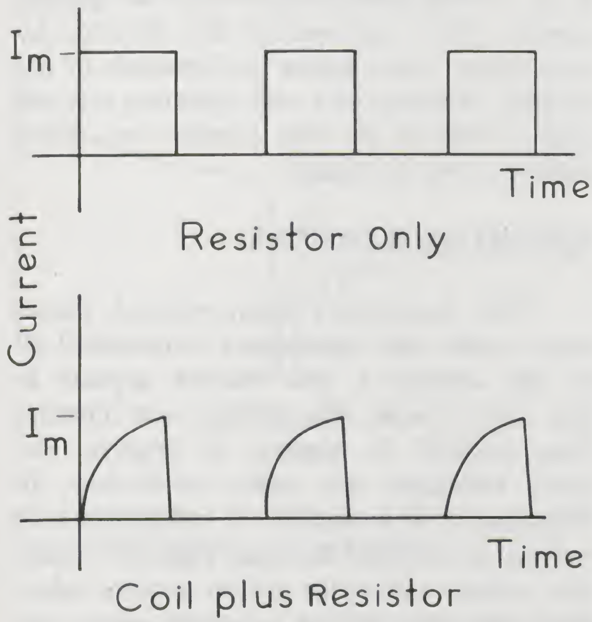

Figure 25.

The coil prevents the current from rising suddenly to its maximum value. Instead the current increases gradually. The coil also prevents a sudden decrease in current as the points open; instead it causes a noticeable arcing across the open points. The arcing was not present with only the resistor in the circuit.

The behavior of the coil is due to its self-inductance. Inductance has the same effect in an electric circuit that mass has in a mechanical system. For example, a large flywheel* resists changes in rotational speed; a coil, having inductance, resists changes in electrical current.

INDUCTANCE RELATED TO FARADAY'S LAW

The behavior of a single coil in an electrical circuit can be explained by using Faraday's Law. Each loop of wire in the coil experiences a magnetic field set up by current flowing in the coil. If the current through the coil changes, the magnetic flux through each loop changes. Whenever this happens, an EMF is included in each loop. Experimentally, the direction of this *self-induced* EMF is such that it opposes the original change in current. The self-induced EMF is often called a "back" EMF, and the experimentally determined rule governing the direction of this EMF is called *Lenz's Law.*

When the points close, the current in the primary circuit of an ignition system starts to increase rapidly. This increase leads to an increase in magnetic flux in the coil, and this induces a "back" EMF. For this reason, the presence of the coil causes the current to increase more gradually than it would if only a resistor were present in the circuit. When the points open, the sudden current decrease induces a very large "back" EMF in the direction of the original current. This back EMF causes arcing across the points and prevents an immediate cutoff of the current.

CAPACITANCE

The capacitor in series with the ballast resistor and in *parallel* with the points produces a different result. In this case, the current rises suddenly when the points close, but decreases gradually when the points open, with no arcing across the points. The resultant waveform is shown in Figure 26.

This action is due to a property called *capacitance.* A capacitor can be compared to a tank into which water is pumped through a pipe at the bottom. If at first the tank is

*A flywheel is a wheel of large mass, usually with a heavy rim, used to reduce speed variations in machinery. Automobile engines have flywheels to smooth out the motion between firings of the plugs.

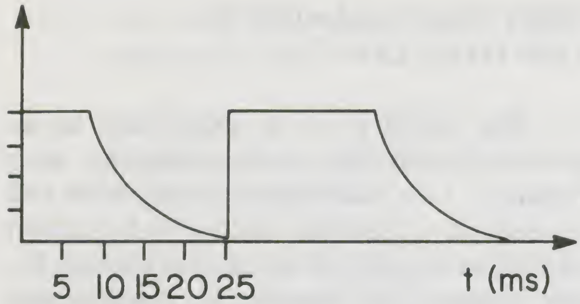

Figure 26.

empty, water rushes freely into it. As the tank fills, the height of water in the tank creates a back pressure which slows the inflow. When the water level in the tank is sufficiently high that the water pressure at the fill pipe equals the supply pressure, no more water flows in. If the tank has a large diameter, much water can enter before its depth becomes great enough to cut off the flow. The tank can then be said to have a large "capacitance" (capacity). Electric charge can be compared to the water, and voltage can be compared to the water pressure.

When the points are closed, current bypasses the capacitor and it remains "empty," or uncharged. When the points open, the current is diverted to the capacitor and starts filling it with charge. As the capacitor fills up, its voltage (analogous to the tank's water pressure) increases, causing the current into the capacitor to decrease. This decrease continues until the capacitor voltage equals the battery voltage of 12 V (analogous to the supply pressure) and the current becomes zero.

To cause the current decrease as the capacitor charges, the resistor is made larger in this circuit than it is in the ignition system. This is comparable to using a smaller pipe to slow down the water flow when the water tank is being filled.

In actual ignition systems, the current decreases to zero more rapidly with both the capacitor and coil in the circuit than with the coil alone. With a coil but no capacitor in the curcuit, a somewhat jagged curve may have been seen, and when the points opened the current went to zero. This irregular shape is due to the irregularity of the arcing across the points. With the capacitor in the circuit, the current is momentarily diverted into the capacitor when the points open. By the time the capacitor is fully charged, the points are too far apart for a spark to jump across them, so that the current drops sharply. This sharp drop is necessary for a good secondary voltage. Without the capacitor, enough arcing occurs to decrease the secondary voltage to a value below that required to cause a good spark at the plugs. The arcing also damages the points very soon.

Problem 1. The oscilloscope trace in Figure 26 shows the voltage versus time for a resistor in series with a capacitor, where the capacitor is in parallel with the points of an ignition system. [You can produce this situation by connecting a wire across the terminals of the primary winding of a coil (shorting out the coil).] What is the time constant associated with the drop in voltage?

CIRCUIT OSCILLATIONS

With resistance (ballast resistor), inductance (coil), and capacitance (condenser) all in the circuit, a new feature appears in the scope traces. The voltage now changes from positive to negative to positive, etc. Such variations are called *oscillations*. In Experiment B-1, significant oscillations in voltage and current show up. Figure 27 shows the voltage across the ballast resistor when both the coil and the capacitor are in the circuit. The voltage (and current) with the points closed looks familiar. Current is bypassing the capacitor (it is "shorted out") and the resistor and coil are in series. This produces the gradual rise in current seen

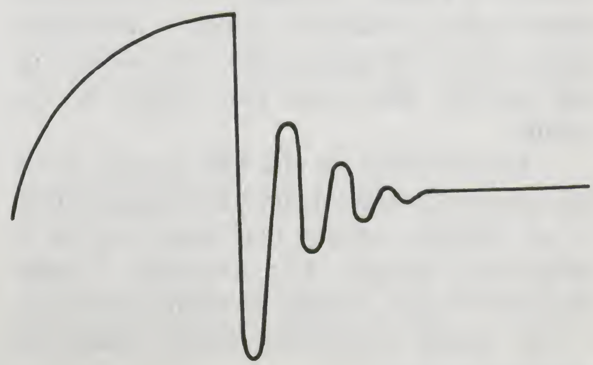

Figure 27.

earlier with the resistor and coil in series. When the points open, the inductance and capacitance act together to produce the oscillations that die out gradually. The time between successive voltage or current peaks is called the *period* of the oscillation. The period for this circuit is typically a few milliseconds.

The same sort of oscillation, with the same period, shows up in the voltage across the primary of the coil, as shown in Figure 28. It should not be surprising to find an oscillation in the voltage across the primary of the coil, since there is an oscillation in the current when the points are open.

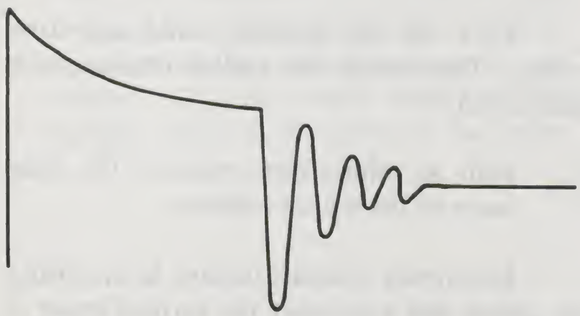

Figure 28.

THE SECONDARY CIRCUIT INTERACTS WITH THE PRIMARY CIRCUIT

In the final part of Experiment B-1, you looked at the voltage across the ballast resistor and across the coil, with the secondary circuit connected through the spark plugs instead of open. Typical oscilloscope traces are shown in Figure 29.

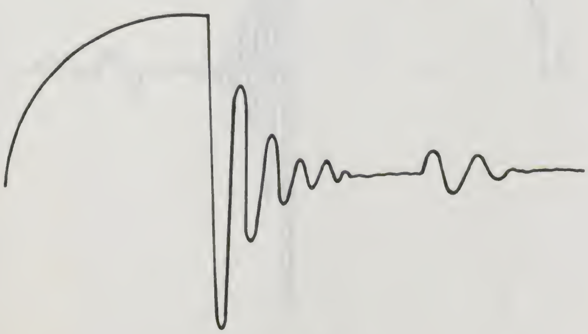

Figure 29.

Another distinctive feature appears here. The trace looks similar to the previous two cases, where the secondary circuit was open and inoperative. But now two distinct oscillations appear during the time the points are open. In this case, a full ignition system in operation, the first oscillation occurs during the time the spark plug is firing while the second oscillation occurs after the secondary circuit has again become inactive. The second oscillation is determined by the value of resistance, capacitance, and inductance in the primary circuit. It is therefore much like the oscillation seen in the previous situations. The important point is that the secondary circuit, when it operates, does affect the primary circuit. The reverse is also true, since the secondary circuit would never have any current at all if the primary circuit did not operate.

Question 6. The graph in Figure 29 shows primary current versus time. Which electrical components are in the primary circuit? Is the secondary circuit open or closed?

MUTUAL INDUCTANCE AND SELF-INDUCTANCE

Interactions between the primary and secondary circuits take place in the ignition coil. A single coil has a property (called self-inductance) which produces an EMF whenever the current in the coil changes.

As shown in Experiment A-2, an EMF can be produced in one coil by changes of the current in another nearby coil (a property called *mutual inductance*). Faraday's Law states that, whenever the magnetic flux through a coil changes, an EMF is induced in the coil; it does not matter whether the flux is from the coil itself or some outside agent.

In the ignition system, a direct relation exists between the properties of the primary circuit and the voltage produced in the secondary circuit. This relationship is of interest because the successful operation of the ignition system depends on the development of high enough voltages in the secondary circuit to produce the spark. Investigate this relationship by doing Experiment B-2.

CAUTION: High voltages are present in this experiment. Be careful not to touch the high voltage connections when the ignition switch is on.

The purpose of this experiment is to determine some of the factors affecting the secondary voltage.

To measure the secondary voltage, you have a *spark-gap voltmeter*. This voltmeter consists of a variable gap calibrated for maximum voltage from the graph shown in Figure 30.

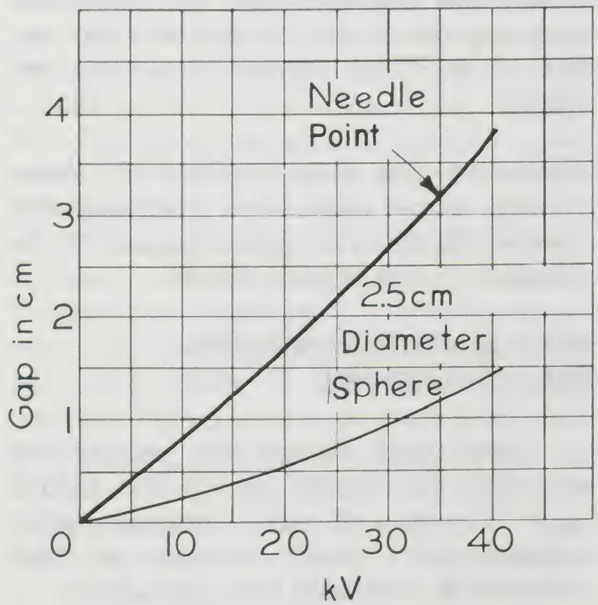

Figure 30.

To use this spark-gap voltmeter, first connect its high voltage terminal to the high voltage terminal of the ignition coil, using one of the high voltage leads. Slide the rubber cover over the connection at the voltmeter. Connect the low voltage terminal of the voltmeter to ground. Pull the plunger of the voltmeter out as far as possible. Set the drive motor at a slow speed and turn the ignition switch on. Slowly push in the plunger until sparks begin to jump between the electrodes. Read the maximum voltage on the scale. This is the "maximum voltage" because, while fluctuations of the secondary voltage are produced by the coil, the spark-gap voltmeter is set so that only the highest voltages present produce a spark.

1. What is the maximum secondary voltage developed at a slow speed?

Set the drive motor control to its greatest speed and measure the maximum secondary voltage.

2. What is the maximum secondary voltage developed at the greatest speed?

Turn off the ignition switch and drive motor. Disconnect the ballast resistor from the circuit.

3. With an ohmmeter, measure the resistance of the ballast resistor.

Reconnect a ballast resistor in the primary circuit and reconnect the vertical input of the oscilloscope across the ballast resistor. Connect the primary to the 12-V battery. Set the drive motor at slow speed and turn on the ignition switch. Push the plunger of the voltmeter in until sparks just begin to occur between the electrodes. Adjust the oscilloscope to give a trace similar to that shown in Figure 31.

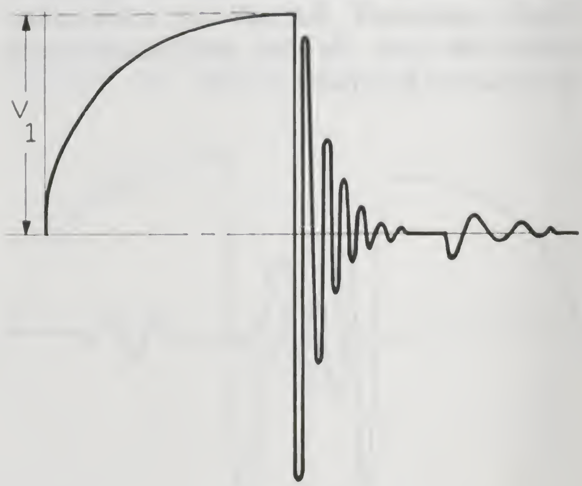

Figure 31.

4. Using the oscilloscope trace, measure the maximum voltage (V_1) across the ballast resistor and, using the spark-gap voltmeter, measure the maximum secondary voltage (V_s). Enter these values in the table.

5. Using a rheostat in series with the primary circuit, change the voltage in the primary and repeat the above measurements. (You might also use different numbers of dry cells in series to get different voltages.) Repeat this procedure for several primary voltages. Enter all data in the table.

6. From the resistance of the ballast resistor and the maximum voltage across it, calculate the maximum current in the primary (I_p) for each value of the voltage. Enter these values in the table.

7. Plot a graph of maximum secondary voltage (V_s) on the vertical axis and values of maximum primary current (I_p) on the horizontal axis.

8. Is this graph a straight line?

9. If it is a straight line, what is the value of the slope of the graph? (Recall that slope is rise divided by run.)

10. What are the units associated with the slope?

11. From the relationship between maximum secondary voltage and maximum values of primary current, can you explain the change in secondary voltage as the speed changes?

PRIMARY CURRENT AND SECONDARY VOLTAGE

As seen in Experiment B-2, the maximum secondary voltage, V_s, is proportional to the maximum primary current, I_p. When the motor runs very fast, the time during which the points are closed (called the *dwell time*) is not long enough for the primary current to build up to its full value. Therefore the induced secondary voltage is not as large as at slower speeds. Figure 32 shows this effect for a typical ignition system.

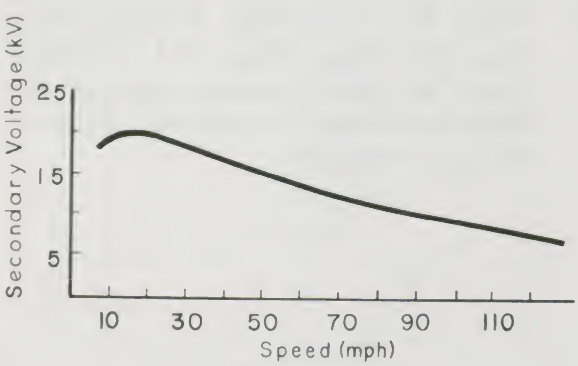

Figure 32.

Problem 2. When an automobile speeds up, the maximum primary current drops from 3.5 A to 3.0 A. If the spark-plug voltage was 25,000 V at the lower speed, what is the new value of voltage?

FUNCTION OF THE BALLAST RESISTOR

The ballast resistor acts to limit the size of the primary current. The resistance of most materials increases as the temperature increases. The ballast resistor uses this effect to limit the current at longer dwell times. When the engine is running at high speed, the primary current does not build up to a large value because of the short dwell time. The value of the ballast resistor is selected to give the appropriate current at these speeds. At lower engine speeds, the longer dwell time and resulting higher current heat the resistor more. This heating increases the resistance and keeps the current from becoming large enough to damage the points.

TWO RESULTS FOR INDUCED EMF

The induced secondary voltage is proportional to the maximum primary current. Experiment A-2 shows that the deflection of the galvanometer needle depends on the rate at which the magnetic field changes. That is, the induced EMF depends on the *rate of change* of the magnetic flux through the coil. The faster the flux changes, the greater the induced EMF. How can these two seemingly different results be combined? It is not too difficult to show that the two results are compatible, if we make some assumptions about relationships between some quantities involved. Although these assumptions seem arbitrary, they are consistent with the results of many other experiments.

DEFINITION OF MAGNETIC FIELD

How can we define magnetic field *quantitatively,* so that we can measure it? One is free to define it in any manner one likes, but it is common practice to define quantities in terms of effects that one can observe. The magnetic force on a straight, current-carrying wire in a magnetic field increases in proportion to the magnetic field (also called *magnetic induction*). This relationship may be expressed in the following form if the wire is perpendicular to the magnetic field

$$F = BIl \qquad (1)$$

where F is the force on the wire, I is the current in the wire, l is the length of wire in the magnetic field, and B is the magnetic field. Equation (1) is valid only when the current is at right angles to the magnetic field. No force is exerted on the wire when the current and magnetic field are in the same direction.

Equation (1) may be used to define the magnetic field. In a given system of units

$$B = F/Il \qquad (2)$$

The preferred units are SI units, where F is in newtons (N), I is in amperes (A), and l is in meters (m). Then the unit of magnetic induc-

tion* becomes a newton/ampere·meter, called a *tesla* (T). A magnetic field of 1 T produces a force of 1 N on a 1-m wire carrying a current of 1 A.

Example Problem. Determine the force on a 10-cm length of wire which is perpendicular to the direction of a magnetic field with a magnetic induction of 0.2 T when the current in the wire is 5 A.

Solution. Given are

$$B = 0.2\ \text{T},\ I = 5\ \text{A, and}$$
$$l = 10\ \text{cm} = 0.1\ \text{m}$$

Substituting into Equation (1)

$$F = BIl$$
$$= (0.2\ \text{N/A·m})(5\ \text{A})$$
$$\times (0.1\ \text{m})$$

or

$$F = (0.2)(0.5\ \text{N/A·m})(\text{A·m})$$

The solution is then

$$F = 0.1\ \text{N}$$

Problem 3. What force is exerted on a 3-cm length of wire that is at right angles to a magnetic field of 0.08 T and carries a current of 1 A?

Problem 4. Find the magnetic induction which exerts a force of 0.06 N on a 7-cm length of wire if the wire has a current of 0.3 A. The wire is perpendicular to the magnetic field.

**Magnetic induction* is usually the name given to a quantity which specifies both the size and the direction of the magnetic field. In this module, we shall use this term interchangeably with "magnetic field."

Question 7. A wire of given length with a fixed voltage across its ends is placed at right angles to a magnetic field. The wire gets hot, and its resistance therefore increases. What happens to the magnetic force on the wire?

DEFINITION OF MAGNETIC FLUX

In Section A we said that the magnetic field could be indicated by the number of field lines per unit area, and the magnetic flux by the total number of lines. Since we can't count the number of imaginary lines, but we do have a definition of magnetic field, it is reasonable to define flux as magnetic field multiplied by the area. In mathematical terms

$$\Phi = B \cdot A \qquad (3)$$

where B is the magnetic field (induction) in teslas, A is the area (in square meters) perpendicular to the direction of B and through which we wish to calculate the flux, and Φ is magnetic flux in units of webers (Wb). A magnetic induction of 1 T gives a magnetic flux of 1 Wb through an area of 1 m^2 perpendicular to the field.

Equation (3) can be reversed to give magnetic induction in terms of flux.

$$B = \Phi/A \qquad (4)$$

This way of expressing B has led to the terminology of *flux density,* which is another term for magnetic field. Older texts use Wb/m^2 for the units of B; 1 Wb/m^2 is identical to 1 T.

Example Problem. What is the magnetic flux in webers through an area of $10^{-3}\ \text{m}^2$, if the magnetic induction (flux density) is 1.5 T?

Solution. Given are

$$B = 1.5\ \text{T} = 1.5\ \text{Wb/m}^2$$
$$\text{and } A = 10^{-3}\ \text{m}^2$$

Substituting into Equation (3) we get

$$\Phi = B \cdot A$$
$$= (1.5\ \mathrm{Wb/m^2})(10^{-3}\ \mathrm{m^2})$$

or

$$\Phi = 1.5 \times 10^{-3}\ \mathrm{Wb}$$

Problem 5. Calculate the magnetic induction in an area of 50 $\mathrm{cm^2}$, if this area contains 1.5×10^{-2} Wb of magnetic flux.

Question 8. The "density" of flux lines is a measure of magnetic induction. Why must it be impossible for two or more such lines to cross each other? (That is, what is the density of lines at the point of intersection?)

FARADAY'S LAW OF ELECTROMAGNETIC INDUCTION

Now that a mathematical definition of magnetic flux is available, Faraday's Law can be expressed more precisely.

If $\Delta\Phi$* represents the change in flux through the space enclosed by a single turn of wire in the time Δt, the *magnitude* (size) of the induced EMF, in volts, is

$$V = \Delta\Phi/\Delta t \qquad (5)$$

where Φ is in webers and t is in seconds. This equation is known as *Faraday's Law of Electromagnetic Induction.* If there are N turns in a coil, the same voltage is induced in each turn, and these voltages add, so that

$$V = N(\Delta\Phi/\Delta t) \qquad (6)$$

Equation (6) shows that, since N is a number without units, and V is in volts, 1 V = 1 Wb/s.

Example Problem. What would be the induced EMF in the secondary winding of the ignition coil of an automobile, if it contains 15,000 turns and the magnetic flux enclosed by the coil changes by 3×10^{-4} Wb in 0.6 ms?

*The Greek letter *delta* (Δ) is often used to represent a *change* or a *difference* in a quantity. Thus $\Delta\Phi$ is a change in Φ.

Solution. Given are

$$\Delta\Phi = 3 \times 10^{-4}\ \mathrm{Wb},\ N = 15{,}000$$

and

$$\Delta t = .06\ \mathrm{ms} = 6 \times 10^{-4}\ \mathrm{s}$$

Substituting these values into Equation (6) gives

$$V = (1.5 \times 10^4)\left[\frac{3 \times 10^{-4}\ \mathrm{Wb}}{6 \times 10^{-4}\ \mathrm{s}}\right]$$
$$= \frac{1.5 \times 3}{6} \times 10^{-4}\ \mathrm{Wb/s}$$

or

$$V = 7.5 \times 10^3\ \mathrm{Wb/s}$$

Since 1 Wb/s = 1 V

$$V = 7500\ \mathrm{V}$$

Problem 6. If the magnetic flux enclosed by a 200-turn coil changes by 2×10^{-3} Wb in 1 s, what will be the induced EMF in the coil?

Question 9. A bar magnet held vertically is dropped through a single loop of wire. The loop is held in a horizontal plane, and the magnet passes right through the center. Sketch a graph of current versus time in the loop.

MAGNETIC FLUX DUE TO CURRENT

We can now understand the results of Experiment B-2. Why is the secondary voltage proportional to the primary current? If the relation between the current in the primary and the magnetic flux it produces is known, then the secondary voltage can be computed from Faraday's Law.

Both the magnetic flux and the magnetic field from a coil are due to the current in the coil. In general, the equation for the magnetic field due to a current depends in a complicated way on the geometry of the

wires and on the substances placed near them. However, in air or in a vacuum, the magnetic field at a point, and the magnetic flux through any area, are proportional to the current, that is,

$$B \propto I \text{ and}$$

$$\Phi = B \cdot A \propto I \tag{7}$$

SELF-INDUCTANCE AND MUTUAL INDUCTANCE

The flux through a coil may be changed in several different ways. One way to change the flux is to move either the coil or the source of the magnetic field. In the ignition coil, the flux changes because the primary current changes. If the flux is proportional to the primary current, the change in flux, $\Delta\Phi$, is proportional to the change in primary current, ΔI_p. That is, if $\Phi_1 = kI_1$, and $\Phi_2 = kI_2$, where k is a constant of proportionality, then

$$\Delta\Phi = \Phi_2 - \Phi_1 = kI_2 - kI_1$$

$$= k(I_2 - I_1) = k\Delta I$$

or

$$\Delta\Phi \propto \Delta I_p$$

Equations (6) and (7) can be then combined to show that

$$V = N(\Delta\Phi/\Delta t) \propto (\Delta I_p/\Delta t) \tag{8}$$

Remember that induced EMFs appear in both the coil carrying the changing current and in a nearby coil. (The magnetic flux through each will be changing.) The ignition coil is actually two coils, consisting of the primary which has about 200 turns and the secondary which has about 15,000 turns. The primary produces the changing magnetic field. Because the induced EMF is proportional to the number of turns (N) in the coil, and the secondary coil has many more turns than the primary, the induced voltage in the secondary coil is much higher than the voltage in the primary coil.

If the voltage in Equation (8) is a self-induced EMF, the constant of proportionality is called the *self-inductance, L.* Thus, if the flux through a coil is proportional to the current in the coil, then the voltage induced in the coil by a change in current is

$$V = -L(\Delta I/\Delta T) \tag{9}$$

The minus sign in Equation (9) is a result of Lenz's Law. It indicates that the induced EMF always tries to oppose any change in the current. If the current decreases, the induced EMF acts to increase it, and if the current increases, the induced EMF acts to decrease it. The unit of inductance is called a *henry* (H) (1 H = 1 V·s/A).

Similarly, suppose that the flux created by a coil is proportional to the current in that coil. Then if two coils are close to each other, changing the current in either coil induces an EMF in the other, and these induced EMF's are related by the following equations:

$$V_2 = -\mathrm{M}(\Delta I_1/\Delta t) \tag{10a}$$

or

$$V_1 = -M(\Delta I_2/\Delta t) \tag{10b}$$

where V_1 is the induced EMF in coil 1 due to a change in the current in coil 2 (ΔI_2) and vice versa. The constant M is called the *mutual inductance.* The same constant, M, is used to calculate the EMF produced in either coil by a changing current in the other. That is, ΔI_1 produces V_2 and ΔI_2 produces V_1, both through the same mutual inductance.

Although a soft iron core present in the ignition coil changes the situation somewhat, the magnetic field is still proportional to the current so that Equations (7), (9), and (10) are still valid.

Example Problem. A coil with a self-inductance of 6×10^{-2} H has a current which changes from 1.5 A to 0.0 A in 0.05 s. What is the magnitude of the EMF induced in the coil?

Solution. Given are

$$L = 6 \times 10^{-2}\ \text{H}$$

$$\Delta I = -1.5\ \text{A}$$

and

$$\Delta t = 0.05\ \text{s}$$

Substituting these values into Equation (9) gives

$$V = -\frac{(6 \times 10^{-2}\ \text{H})(-1.5\ \text{A})}{5 \times 10^{-2}\ \text{s}}$$

or

$$V = 1.8\ \text{H}\cdot\text{A/s}$$

Since 1 H = 1 V·s/A, the solution becomes

$$V = 1.8\ (\text{V}\cdot\text{s/A})\cdot(\text{A/s})$$

or

$$V = 1.8\ \text{V}$$

Problem 7. A coil with a self-inductance of 10 H has a current which changes from 0.2 A to 0.1 A in 0.01 s. What is the magnitude of the EMF induced in the coil?

SECONDARY VOLTAGE

The secondary and primary coils in the ignition system interact through mutual inductance. Equation (10a) is the formula for the induced secondary voltage if ΔI_1 is the change in the primary current, Δt is the time for that change, and M is the mutual inductance between the primary and secondary coils. When the points open, the primary current, I_p, decreases to zero in a time Δt. Then the change in current is

$$\Delta I_1 = \text{final current} - \text{initial current}$$

or

$$\Delta I_1 = 0 - I_p = -I_p \qquad (11)$$

Combining (10a) and (11) for secondary voltage, V_s, gives

$$V_s = (M/\Delta t)I_p \qquad (12)$$

The mutual inductance M is constant. The value of Δt is determined by the time necessary for the discharge of the capacitor in the primary. This time depends on the value of the capacitor used, and is constant for any particular capacitor. Thus, the quantity $M/\Delta t$ is constant, and $V_s \propto I_p$ is consistent with your observations in Experiment B-2.

Problem 8. Calculate the induced EMF in the secondary of a coil with a mutual inductance of 0.06 H if the primary current increases by 2 A in 0.01 s.

Problem 9. How quickly must the current in the primary of a coil go from 5 A to 0 A, if the average voltage induced in the secondary is 1000 V and the coil has a mutual inductance 0.2 H?

Question 10. The current in a coil is increasing at a certain rate. If a nearby coil has its ends connected together, so that it can carry a current, what happens to the current in the first coil?

CAPACITANCE

An important feature of the distributor is the capacitor which is connected across the breaker points. This capacitor prevents arcing across the points as they open. Such an electric arc causes excessive wear of the points, and also reduces the rate of change of the primary current, thereby reducing the induced EMF in the secondary.

Any pair of conductors placed near each other form a capacitor and are said to have *capacitance.* Capacitance is a measure of the ability to store charge. Suppose that electric charge is transferred from one conductor to another, so that one conductor acquires a net positive charge Q and the other an equal negative charge $-Q$. Charging the conductors

creates a *potential difference* ("voltage") between them, with the positively charged conductor having the higher potential. The potential difference V is proportional to the amount of charge Q. The constant of proportionality is called the capacitance C, so that

$$V = CQ \tag{13}$$

This equation is a definition of electric capacitance. The units of capacitance are *farads* (1 F = 1 C/V). The capacitance of a pair of conductors depends only on their geometry, orientation, and on the material which separates them. One farad is an extremely large unit of capacitance, and capacitors in the microfarad (μF) or picofarad (pF) ranges are commonly used. The capacitor (condenser) in an ignition system consists of two long strips of metal foil with a strip of insulating material between them. The resulting sandwich is rolled up and put into a little can.

Example Problem. Determine the capacitance of a capacitor which has a charge of 5×10^{-2} C, when the potential difference across it is 500 V.

Solution. Given are

$$Q = 5 \times 10^{-2}\ \text{C}$$

$$V = 500\ \text{V}$$

Substituting these values into Equation (13) gives

$$C = (5 \times 10^{-2}\ \text{C})/(5 \times 10^{2}\ \text{V})$$

or

$$C = 1 \times 10^{-4}\ \text{C/V}$$

Since 1 F = 1 C/V, the solution may be written as

$$C = 1 \times 10^{2} \times 10^{-6}\ \text{F}$$

Recalling that 10^{-6} F = μF

$$C = 100\ \mu\text{F}$$

Problem 10. What is the capacitance of a capacitor which has a charge of 6×10^{-3} C, when the potential difference across it is 150 V?

Problem 11. The starting capacitor on an electric motor is 400 μF. If the maximum potential difference across it is 220 V, what is the maximum charge stored in the capacitor?

Question 11. From what you know about electric forces, would it be easier or harder to place opposite charges on two parallel plates when they are close together than further apart? What does this mean in terms of capacitance?

SUMMARY

This section showed that a coil in a circuit has a property known as *inductance.* The inductance resists any change in current, just as a flywheel resists changes in engine speed. Inductance is due to Faraday's Law; the magnetic flux due to the coil changes and induces an EMF in the coil itself. Since the coil induces the EMF in itself, this property is sometimes called *self-inductance, L.*

The capacitor acts like a storage tank for charge, and prevents arcing across the points when they open. Because of the capacitor, the current and magnetic field change more rapidly when the points open than they would with the coil alone. The faster change in primary current causes a higher induced secondary voltage. The prevention of arcing also reduces wear of the points.

An inductance and capacitance in a circuit can produce oscillations in the voltage and current. Current in the secondary affects the primary circuit, causing a second oscillation when the points open.

The ability of one coil with a changing current to induce an EMF in another nearby coil is called *mutual inductance, M.* The primary and secondary circuits of the ignition

system interact through the mutual inductance of the two coils. These coaxially wound coils are built into one housing called the *ignition coil.*

Finally, the induced secondary voltage is proportional to the maximum primary current. Symbolically:

$$V_s \propto I_p$$

The time during which the points are closed is called *dwell time,* and it directly affects the primary current. A longer dwell time allows a larger primary current to build up. Higher engine speeds produce shorter dwell times which in turn produce smaller primary currents. The smaller primary currents induce smaller secondary voltages. The ballast resistor helps to smooth over this effect by limiting the current in the primary more at shorter dwell times. It does this because its resistance is higher at the higher temperatures associated with longer dwell times.

You have learned several definitions and laws of physics which relate to the ignition system.

Definition of Magnetic Inductance, B

$$B = F/Il$$

where F is the force on a wire of length l carrying a current I. If B is teslas, F must be in newtons, I in amperes, and l in meters.

Definition of Magnetic Flux, Φ

$$\Phi = B \cdot A$$

where B is the magnetic induction and A is the cross-sectional area through which the magnetic lines pass. For Φ in webers, B must be in teslas and A in square meters.

Faraday's Law

$$V = \Delta\Phi/\Delta t$$

V is the induced EMF in volts, where $\Delta\Phi$ is a change in magnetic flux in webers and Δt is the time in seconds required for the flux to change.

Lenz's Law

Lenz's Law states that an induced current is in a direction which opposes the cause which produces it. Faraday's Law can be written to take into account Lenz's Law by using a negative sign. Thus, the combined law becomes

$$V = -(\Delta\Phi/\Delta t)$$

Definition of Self Inductance

When the magnetic flux around a conductor (usually this means the flux passing through the center of a coil) is proportional to the current in the conductor (as it always is unless an iron core strongly influences the magnetism), Faraday's Law and Lenz's Law combine to become the proportion

$$V \propto -(\Delta I/\Delta t)$$

If this proportion is written as an equation,

$$V = -L(\Delta I/\Delta t)$$

The proportionality constant is defined as the *self-inductance* of the conductor (usually a coil). For L to be in henries, I must be in amperes, t in seconds, and V in volts.

Definition of Mutual Inductance

When the magnetic flux around one conductor (usually this means the flux passing through the center of a coil) is produced by another nearby conductor (usually another coil), Faraday's Law and Lenz's Law combine to give

$$V_2 \propto -M(\Delta I_1/\Delta t)$$

the proportionality constant is defined as the

mutual inductance between the two conductors (or coils).

Since you can call either coil, "coil one" or "coil two," we could also write this equation as

$$V_1 = -M(\Delta I_2/\Delta t)$$

Definition of Electric Capacitance, C

Electric capacitance is defined by the equation

$$C = Q/V$$

where Q is the electric charge which has been moved from one conductor to the other, and V is the voltage between the two conductors. For C in farads, Q must be in coulombs and V in volts.

GOALS FOR SECTION C

The following goals state what you should be able to do after you have completed this section of the module. The example which follows each goal is a test item which fits the goal. Answers to the items immediately follow these goals.

1. *Goal:* Be able to calculate the time constant of an *L-R* circuit, an *R-C* circuit, or an *L-R-C* circuit.

   Item: A 4-Ω resistor and 0.15 μF capacitor are connected in series. If the capacitor is initially charged, how long does it take to discharge to 36.8 percent of its initial value?

2. *Goal:* Be able to calculate the period of oscillation of an *L-C* or *L-R-C* circuit.

   Item: What is the period of an oscillating circuit containing 0.1 μF of capacitance and 5 mH of inductance?

3. *Goal:* Be able to calculate the mutual inductance of two coils from their self-inductances.

   Item: If the primary of an ignition system coil has a self-inductance of 0.9 mH and the secondary coil has a self-inductance of 70 H, what is their mutual inductance?

4. *Goal:* Be able to calculate the mutual inductance between a primary coil and a secondary coil, from an oscilloscope trace of the voltage across the primary coil and another oscilloscope trace of the voltage across a known resistor connected in the secondary circuit.

   Item: The scope trace depicted in Figure 33a shows the voltage across the primary coil of an ignition system. The scope trace in Figure 33b showns the voltage across a 10-Ω resistor between the low voltage end of the spark gap and ground. What is the mutual inductance between the primary and secondary coils?

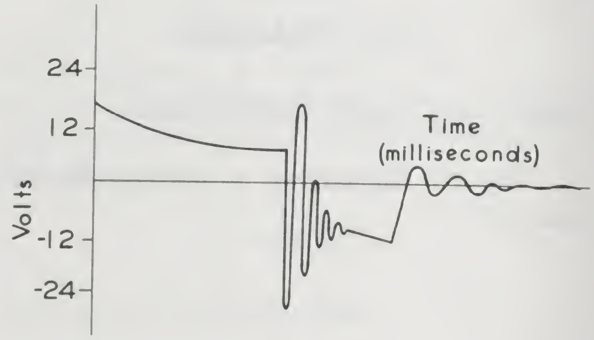

Figure 33A.

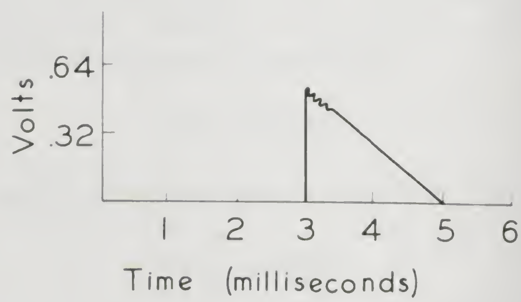

Figure 33B.

5. *Goal:* Be able to calculate the "effective" primary inductance of a coil which has a secondary circuit which is conducting, from a scope trace of voltage across a resistor in the primary circuit.

   Item: The scope trace shown in Figure 34 is the voltage across the ballast resistor in a primary circuit of an ignition system. With a resistance of 4 Ω find the "effective" inductance of the primary coil while the secondary circuit is conducting.

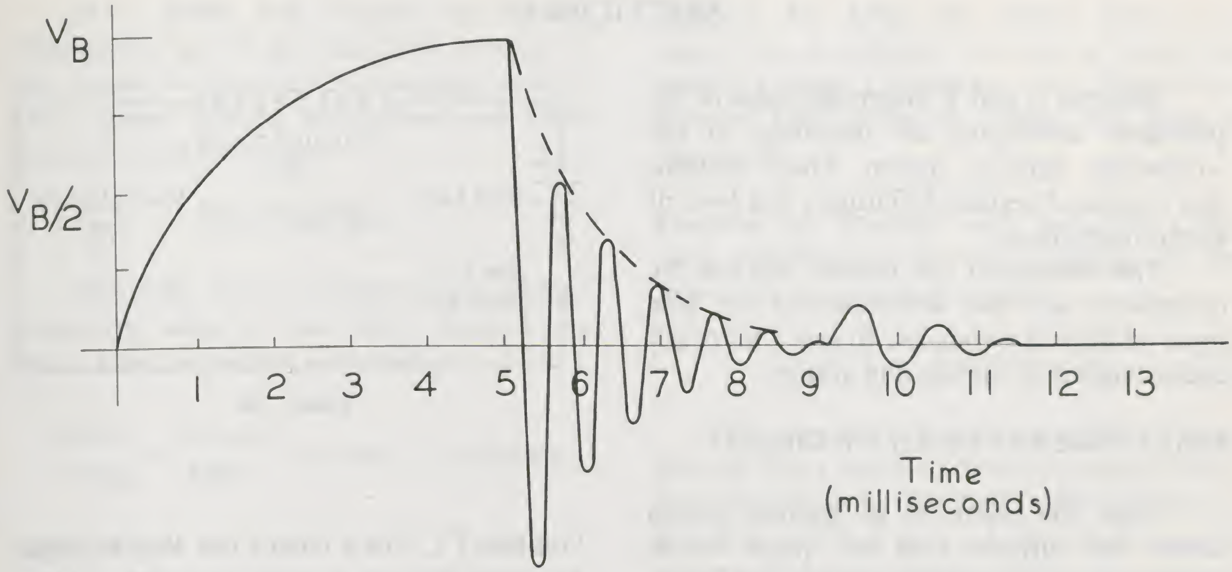

Figure 34.

Answers to Items
Accompanying Previous Goals

1. 0.6 μs

2. 14 ms

3. 0.25 H

4. ≈ 0.5 H

5. $\approx 2 \times 10^{-3}$ H

SECTION C

Sections A and B illustrated some of the principles underlying the operation of the automobile ignition system. These sections also explained certain definitions and laws of electromagnetism.

This section of the module will use the definitions and laws developed so far, plus some additional principles, to give a thorough understanding of the ignition system.

TIME CONSTANT OF AN *L-R* CIRCUIT

When the points of an ignition system close, the current does not jump to its maximum value immediately. Instead it builds up as shown in Figure 35. With the points closed, current bypasses the capacitor and the capacitor is said to be "shorted." The primary circuit is then essentially as diagrammed in Figure 36.

In this circuit, the resistance is made up of the ballast resistor, the resistance of the primary coil, and the *internal resistance* of the battery. The circuit shown in called an *L-R series* circuit. If the switch has just been closed, the current increases from zero and approaches a constant value.

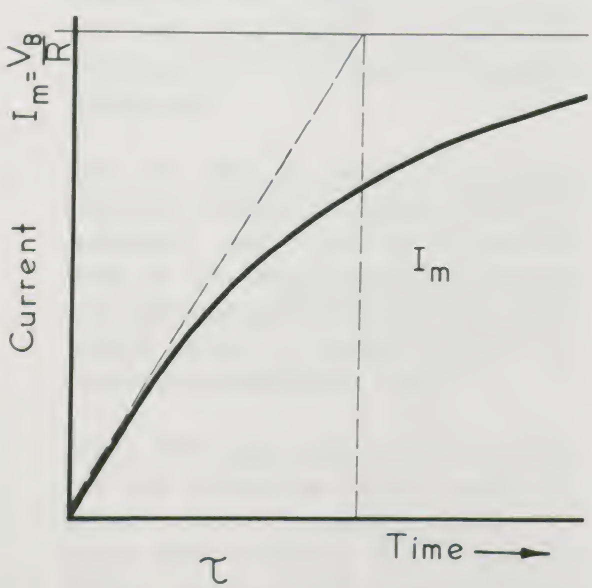

Figure 35.

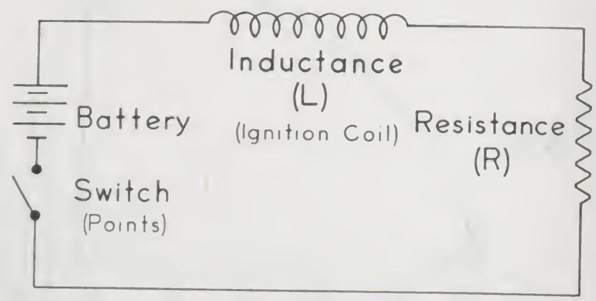

Figure 36.

Problem 12. For a circuit like that in Figure 36, show that the maximum current will have a value of V_B/R, where V_B is the total voltage of the battery and R is the total resistance of the circuit. (When the current reaches a steady value, the inductance no longer has any effect on it—only changing currents are affected.)

If we sum the resistances of an ignition system primary circuit, we have for the total resistance

$$R_P + R_B + R_I = R$$

where R_P is the primary coil, R_B is the ballast resistance, and R_I is the internal resistance of the battery. Typical values of these quantities are

$$R_P = 1.47\ \Omega$$

$$R_B = 1.95\ \Omega$$

$$R_I = 0.03\ \Omega$$

for a total of

$$R = 3.45\ \Omega$$

Problem 13. What is the value of the maximum current in an ignition system having a total resistance of 3.45 Ω and a battery voltage of 12 V?

In a series L-R circuit, the battery voltage may not be the only EMF present. If the current in the circuit is changing, another EMF arises. This is the self-induced EMF given by Faraday's Law:

$$V = -L(\Delta I/\Delta t)$$

This EMF must be added to the applied voltage in order to use Ohm's Law. Using Ohm's Law, we get the equation,

$$\begin{matrix}\text{battery} \\ \text{voltage}\end{matrix} + \begin{matrix}\text{induced} \\ \text{EMF}\end{matrix} = \text{current} \times \text{resistance}$$

or, in symbols

$$V_B + V_P = IR \qquad (14)$$

The induced voltage, V_P, is given by

$$V_P = -L_P(\Delta I_P/\Delta t)$$

where L_P is in the self-inductance of the primary coil. Thus Equation (14) becomes

$$V_B + [-L_P(\Delta I_P/\Delta t)] = IR \qquad (15)$$

or

$$V_B - L_P(\Delta I_P/\Delta t) = I_P R \qquad (16)$$

The sign of the induced EMF is different from that of the battery voltage. This means that, when the current is increasing, the battery voltage V_B is *reduced* by the induced EMF, so that the net voltage is *less* than the battery voltage. When the current is increasing, it is not as large as it would be with the battery voltage alone across the same resistance.

Problem 14. At the instant when the points of an ignition system close, the current I is zero. Using this fact, plus Equation (14), find the value of the induced EMF at the instant when the points close for an ignition system containing a battery whose voltage is 12 V.

Problem 15. After the points have been closed for a sufficient interval of time, the current reaches a maximum value. What is the induced EMF when the current has reached this value?

Problem 16. Starting with Equation (15), show algebraically that the equation can be solved for L_P, giving the result,

$$L_P = (V_B - I_P R)/(\Delta I_P/\Delta t) \qquad (17)$$

The denominator of Equation (17) is $\Delta I_P/\Delta t$. On a graph of primary current versus time, ΔI_P is a current "rise" for a a corresponding "run" of time Δt. For small enough values of Δt the ratio $\Delta I_P/\Delta t$ is approximately the slope of the curve at the particular time we have chosen. In fact, instead of $\Delta I_P/\Delta t$ the more precise quantity to use would be the slope of the curve. Then Equation (17) can be written in the form,

$$L_p = \frac{V_B - I_P R}{(\text{slope of } I \text{ vs. } t \text{ curve})} \qquad (18)$$

At the instant when the points close (at time $t = 0$), $I_P = 0$; therefore, $I_P R = 0$, and the inductance can be found from the simpler equation

$$L_P = \frac{V_B}{(\text{slope of } I \text{ vs. } t \text{ curve at } t = 0)} \qquad (19)$$

To apply Equation (19) look at the graph in Figure 37. A dashed line is drawn tangent to the curve at $t = 0$ (at the origin) and is extended until it meets the horizontal line representing maximum current. Another dashed line is then drawn from that intersection down to the horizontal time axis. The slope of a curve at a point on the curve is defined as the same as the slope of the straight line which is tangent to the curve at that point. Thus, the slope of this curve at $t = 0$ is the slope of the dashed line. Then the slope has a "rise" of I_m and "run" of τ, where τ is a certain time interval. The slope is therefore I_m/τ.

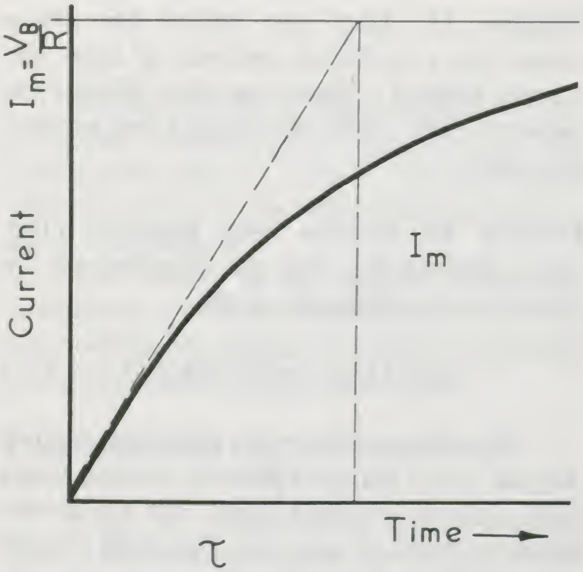

Figure 37.

If Equation (19) is written in terms of these quantities, then

$$L_P = V_B/(I_m/\tau)$$

or

$$L_P = \tau(V_B/I_m) \qquad \text{(Time constant of } L\text{-}R \text{ circuit)}$$

Using Ohm's Law, the battery voltage V_B divided by the maximum current I_m is just the total resistance of the circuit, R. Thus we have

$$L_P = \tau R$$

or

$$\tau = L_P/R \qquad (20)$$

This time interval, τ, is an important characteristic of an *L-R* circuit. It is called the *time constant* because for *any* *L-R* circuit, the current builds to the same fraction (63.2 percent) of its maximum value in the time interval calculated from the ratio of the inductance to the resistance (L/R). The time constant provides a convenient way to discuss the build-up of current in a circuit containing an inductance. After one time constant the current has increased to about 63 percent of its final value. After three time constants, the current has increased to about 95 percent of its final value and after five time constants, to about 99 percent of the final value.

Example Problem. The primary inductance of an ignition coil is 7×10^{-3} H and the total resistance in the primary circuit is 4 Ω. In a 12-V system, what is the maximum value of current in the primary, and what is the time constant for the circuit?

Solution. Given are

$$L = 7 \times 10^{-3} \text{ H}$$

$$V_B = 12 \text{ V}$$

$$R = 4\ \Omega$$

For the maximum current, we can use Ohm's Law. We have

$$I_m = 12 \text{ V}/4\ \Omega$$

or

$$I_m = 3 \text{ A}$$

To find the time constant, we use Equation (20), giving

$$\tau = (7 \times 10^{-3} \text{ H})/(4\ \Omega)$$

Simplifying this expression gives

$$\tau = 1.2 \times 10^{-3} \text{ H}/\Omega$$

Since 1 H = 1 Ω·s

$$\tau = 1.2 \times 10^{-3}\ (\Omega\cdot\text{s})/(\Omega)$$

$$= 1.2 \times 10^{-3} \text{ s}$$

or

$$\tau = 1.2 \text{ ms}$$

The current builds to 63.2 percent of its maximum value in this time.

Problem 17. If the inductance of a coil is 2×10^{-2} H and the circuit containing the inductance has a resistance of 0.5 Ω, what is the time constant for this circuit?

Question 12. A coil of wire has a certain inductance, resistance, and time constant. What happens to the time constant when the temperature of the wire is increased?

TIME CONSTANT OF AN *R-C* CIRCUIT

Experiment B-1 demonstrated that the current in a circuit with both capacitance and resistance also changed gradually. When the points opened, the current dropped to about 37 percent of its initial maximum value in a time which can be called a time constant. An analysis similar to the one for an *L-R* circuit would show this time constant to be

$$\tau = RC \qquad (21)$$

(Time constant of *R-C* circuit)

where R is in ohms, C in farads, and τ in seconds. Although at first it may appear to differ in meaning from the *L-R* time constant, it has precisely the same meaning. After one time constant, the current has decreased by 63 percent of its maximum value to 37 percent of its maximum value. After three time constants, the current has decreased by 95 percent of its maximum value to 5 percent, etc. (This similar analysis for the *L-R* and the *R-C* circuits is possible because both produce curves belonging in the category of *exponential curves,* and the analysis is the same for all such curves.)

Problem 18. An ignition system primary circuit has a resistance of 3.45 Ω. If the capacitor has a value of 2×10^{-7} F, what is the time constant for this circuit?

Problem 19. What is the time constant for a circuit consisting of a 1200-Ω resistor in series with an 0.25 μF capacitor?

OSCILLATING CIRCUITS

With both capacitance and inductance in the primary circuit, you saw oscillations in primary current when the points opened.

We can see how this oscillation occurs by means of an analogy. Suppose that the capacitor is represented by a large tank consisting of two sections, as shown in Figure 38. Having more water in one side of the tank than in the other, as shown in Figure 38, is like a capacitor having one positively charged plate and one negatively charged plate.

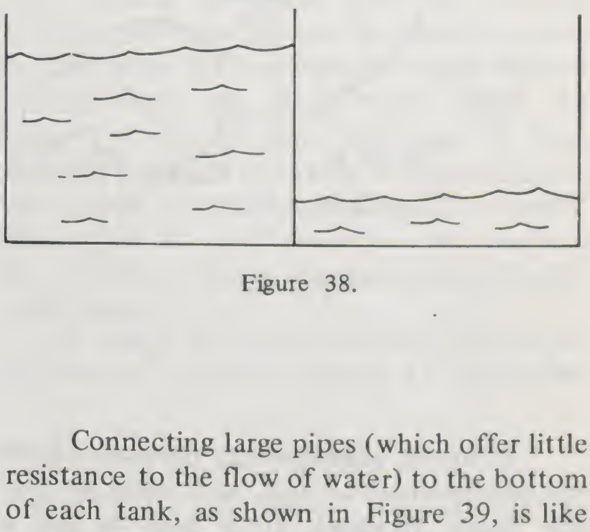

Figure 38.

Connecting large pipes (which offer little resistance to the flow of water) to the bottom of each tank, as shown in Figure 39, is like connecting low-resistance wires to each terminal of the capacitor. These pipes are connected so that water flowing from one tank to the other causes a paddle wheel to turn. The paddle wheel turns a flywheel which is mounted on the same shaft.

The difference in water levels between the two sides on the tank provides a pressure difference. This pressure difference is similar to the voltage (potential difference) between two capacitor plates when the capacitor is charged. The valve is analogous to the switch in an electrical circuit.

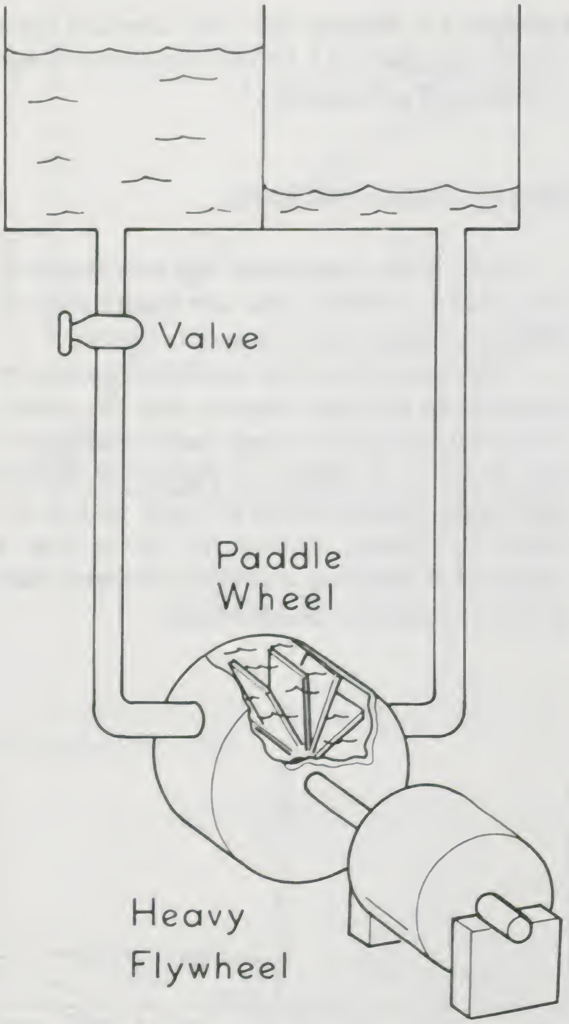

Figure 39.

A flow of water through the pipes causes the paddle wheel to turn. As it turns, so does the heavy flywheel. It is hard to get a flywheel to rotate, but once it is rotating, it is hard to stop it again. The paddle wheel exerts a "back pressure" on the water when the water current begins to flow. When the water levels are the same on the two sides, and the water current would normally stop, the flywheel continues to turn and the paddle wheel tries to keep the water flowing at a constant speed. The flywheel-paddle wheel combination influences water current just like an inductance influences electric current.* This mechanical device has "inductance." It is like an *L-C* circuit in electricity. What happens when the water valve is opened?

When the valve is opened, the pressure difference creates a flow of water through the paddle-wheel arrangement which raises the water level in the other side of the tank. Since the flywheel system opposes the changing water current, that current builds up slowly. As the current increases, the flywheel spins faster.

When the water levels in the two sections of the tank become equal, the flywheel is still turning, as shown in Figure 40. In fact, it is now turning at its highest rate. As the

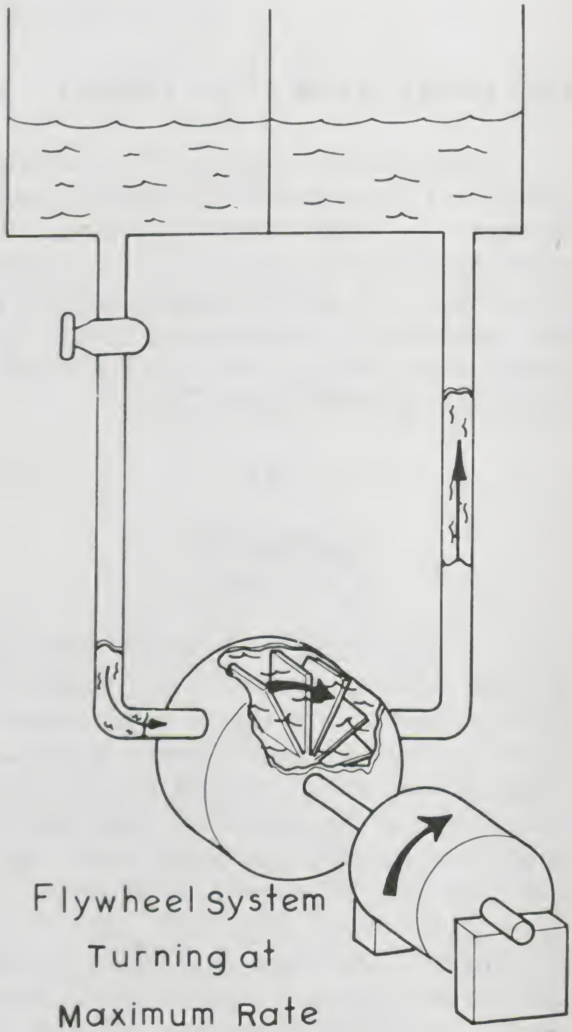

Figure 40.

*This is not quite a perfect analogy. The water itself, due to its own mass, also resists speeding up and slowing down. Electric charges in wires also possess mass, but their resistance to changes in speed is quite negligible compared to inductance effects.

flywheel slows down the paddle wheel continues to pump water into the right-hand side of the tank, with the wheel slowing down in the process. Finally the flywheel stops turning and, when it does, the difference in water levels is the same as we started with, except that it now is higher on the right. This is shown in Figure 41.

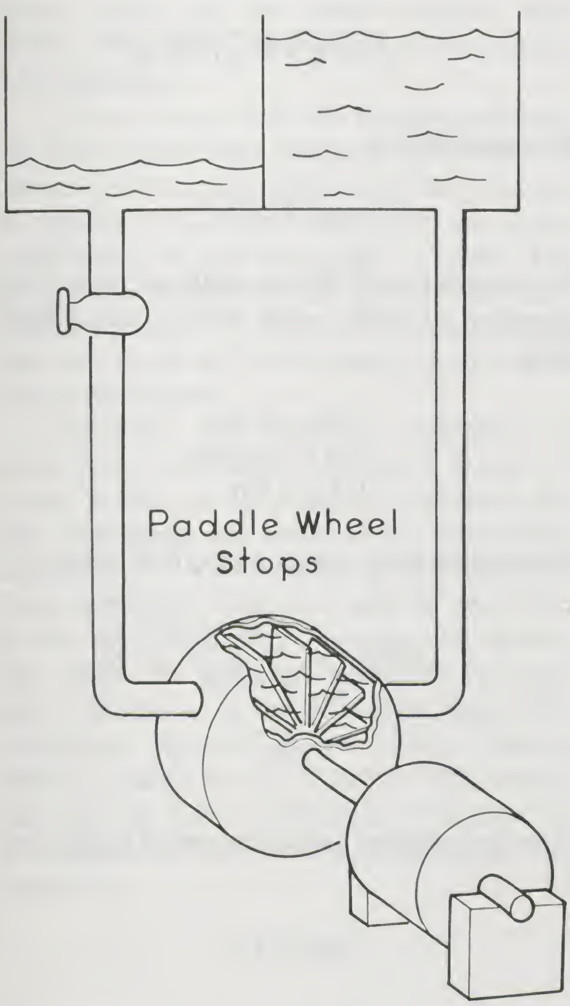

Figure 41.

Now the pressure difference will cause the paddle wheel to turn in the other direction, and the whole process is repeated until the left once again has the higher level. This *oscillation* of water back and forth between the two sides of the tank would go on forever if no friction were present. With friction present, the oscillation occurs, but slowly "dies out." Eventually the water levels are equal and the flywheel is no longer rotating.

Now let us consider an *L-C* circuit. Begin with a charged capacitor (which has more electrons on one plate than on the other) and close the switch. The potential difference between the plates causes the surplus electrons in the negatively charged plate to move through the circuit to the positively charged capacitor plate (which has a deficit of electrons). Because the inductance opposes the change in current, the current increases gradually. At some point in time, the capacitor is fully discharged, with both plates having zero net charge. This occurs at the same time the current through the inductance reaches its maximum value. Just as the inductance opposed the build-up of current through it, it opposes any decrease in the current through it. It thus acts as a source of EMF. As the current gradually decreases, an excess of negative charge is built up on the capacitor plate which was initially positively charged. The process continues until the current through the induction has decreased to zero. At this time, the capacitor has again become charged, and the cycle repeats, with the current in the opposite direction. If there were no electrical resistance in the circuit, the oscillations of charge would continue indefinitely. But, like friction in the water analogy, the resistance causes the oscillations to gradually die out.

A graph of current versus time for an *L-C* circuit is shown in Figure 42. This is the

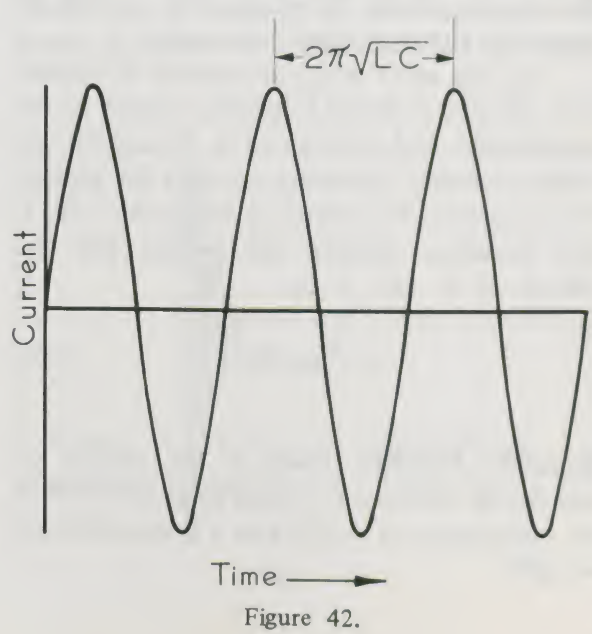

Figure 42.

same as the graph of water current versus time in the analogy we described. It is also similar to the graph of speed versus time for a child on a swing (if there is no friction). In fact, any simple motion in which oscillations occur and for which friction can be neglected may be represented by this sort of graph. If you have ever studied trigonometry, you may recognize this as being similar to a graph of the sine function. For an *L-C* circuit with no resistance, it is exactly a graph of a sine function.

One important feature of the oscillation of an *L-C* circuit is the *period of oscillation.* In the case of the water analogy, the period is the time it takes for the water to move from one section of the tank to the other and back to the original levels again. In the case of the *L-C* circuit, the *period* is the time it takes for the capacitor to discharge through the inductance, to charge in the opposite sense, to discharge back through the inductance and to be restored to its original charge.

The period of oscillation for the water system depends upon the size of the tank of water and on the inertia of the flywheel. For a small tank, the water will oscillate back and forth faster than for a tank of larger capacity, but with the same water levels. A smaller flywheel allows the water to move faster and thus makes the period shorter than for a larger flywheel. The period is in some way related to both the capacity of the tank and the inertia of the flywheel. The period increases as either of these is increased.

In the same way, the period of oscillation of an *L-C* circuit is directly related to the capacitance and inductance in the circuit. As either quantity increases, so does the period. If the period in seconds is designated by T, the equation relating the period and the values of L and C is,

$$T = 2\pi\sqrt{LC} \qquad (22)$$

Example Problem. What is the period of oscillation for an *L-C* circuit in which there is an inductance of 2.0 H and a capacitance of 4.5 μF?

Solution. Given are

$$L = 2.0 \text{ H and}$$
$$C = 4.5 \times 10^{-6} \text{ F}$$

Substituting these values into Equation (22) we have

$$T = (2)(3.14) \times$$
$$\sqrt{2 \times 4.5 \times 10^{-6} \text{ H}\cdot\text{F}}$$

The result then is

$$T = 18.8\sqrt{\text{H}\cdot\text{F}}$$

To show that $\sqrt{\text{H}\cdot\text{F}}$ has units of time, it is necessary to recall some earlier unit definitions,

$$1 \text{ F} = 1 \text{ C/V}$$
$$1 \text{ H} = 1 \text{ V}\cdot\text{s/A}$$
$$1 \text{ A} = 1 \text{ C/s}$$

Substituting these values into $\sqrt{\text{H}\cdot\text{F}}$ gives

$$\sqrt{\text{H}\cdot\text{F}} = \sqrt{\frac{\text{V}\cdot\text{s}}{\text{C/s}} \times \frac{\text{C}}{\text{V}}}$$
$$= \sqrt{\text{s}^2} = \text{s}$$

Thus the solution for the period of oscillation is

$$T = 18.8 \text{ s}$$

Problem 20. If it had no resistance, what would be the period of oscillation for the primary circuit of an automobile ignition system? The inductance is 7×10^{-3} H, and the capacitance is 0.1 F.

Question 13. Suppose an *L-C* circuit has a fixed capacitor and an air-coil inductor. What happens to the frequency of oscillation, when an iron core is inserted into the coil?

Problem 21. Determine the frequency of oscillation for an *L-C* circuit in which the inductance is 1.2×10^{-2} H and the capacitance is 0.3 μF.

L-C CIRCUITS WITH RESISTANCE

In the actual primary circuit there is resistance, as there must be in any real *L-C* circuit. Even if the ballast resistor were absent, the other components of the circuit have resistance.

In our water tank and flywheel analogy, the water pipes offer resistance to the flow of water. Friction is also present in the bearings of the flywheel. These resistances cause the oscillations to die out after a time. The greater the resistance, the quicker the oscillations die out. A child on a swing moving back and forth will also come to a stop after several oscillations.

Likewise, the electrical resistance of wires causes electrical oscillations in an *L-C* circuit to die out. If no resistor is present, the only resistances are those of the connecting wires and the wire making up the inductor. Their combined resistance may be very low, so the oscillation may die out very slowly. But when the inductor resistance or some other resistance in the circuit is larger, the oscillations die out more quickly. Such a circuit is called an *L-R-C* circuit. The time it takes for an *L-R-C* oscillation to "decay" to 36.8 percent of its initial maximum value (τ_d) is given by

$$\tau_d = 2\,L/R$$

(Remember that the time constant for the decay in an *L-R* circuit is just L/R.)

With the points open, the primary circuit of an ignition system is equivalent to that shown in Figure 43. It is called an *L-R-C* circuit.

Figure 44 shows a graph of current versus time for an *L-R-C* circuit immediately following connection of the battery. A similar graph could show the current in our water-tank analogy or the speed of a child on a swing.

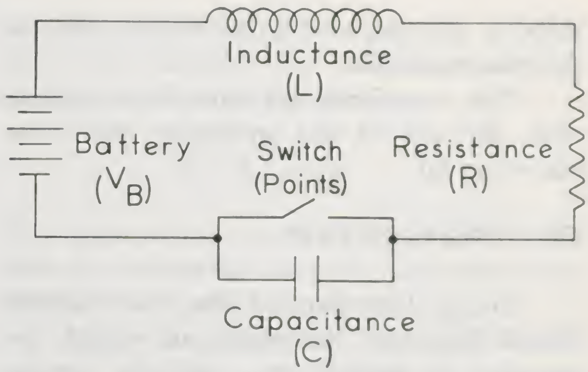

Figure 43.

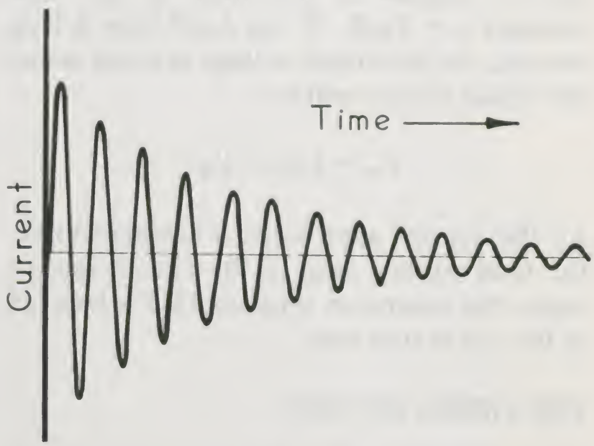

Figure 44.

OPERATION OF AN IGNITION SYSTEM

Experiment B-1 showed that the oscilloscope trace of the voltage across the ballast resistor as a function of time appeared as shown in Figure 45. This trace has the same

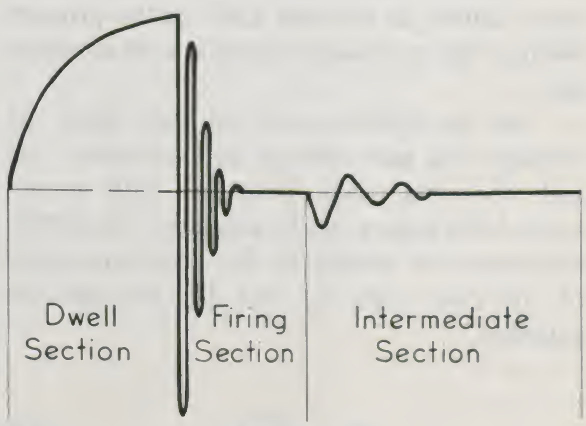

Figure 45.

shape as the graph of current versus time in the primary circuit.

This waveform can now be explained with the aid of the principles you have learned so far.

THE DWELL SECTION

During that part of the trace labeled "Dwell Section," the points are closed, the capacitor is shorted out, and the current builds up as in a typical *L-R* circuit. The current increase is described by the time constant $\tau = L_P/R$. If the dwell time is long enough, the maximum voltage reached across the ballast resistor will be

$$V_m = I_m R = V_B$$

As the current approaches a constant value, the total voltage drop in the circuit appears across the resistance, since no EMF is induced in the coil at that time.

THE FIRING SECTION

The "Firing Section" of the cycle begins the instant the points open. Figure 45 shows the current breaking into the rapidly decaying oscillation which is typical of an *L-R-C* circuit. The period of oscillation indicates an "effective" inductance (L_{eff}) for the primary coil which is much less than the self-inductance of the primary. This lower effective inductance is due to the coupling of the primary coil to the secondary coil through their mutual inductance. The mutual inductance causes an induced EMF in the primary because the secondary circuit is now conducting.

In the ignition coil, all flux from the primary coil goes through the secondary coil and vice-versa, since they are both wound around the same core. In this case, the mutual inductance is related to the self-inductances of the two coils, L_1 and L_2, through the equation,

$$M = \sqrt{L_1 L_2} \tag{23}$$

Problem 22. If the self-inductance of the primary coil in an ignition system is 5 mH and the self-inductance of the secondary is 50 H, what is the mutual inductance of the pair?

The oscillating current in the primary dies out before the spark plug stops firing. The measured time for this oscillation to decay to 36.8 percent of its initial maximum value is the decay time, τ_d. By using the equation, $\tau_d = 2\, L_{eff}/R$, and knowing the primary resistance, we can calculate the effective inductance.

When the points open, the battery charges the capacitor to the same voltage as the battery. Since the direction of this capacitor voltage is equal and opposite to the battery voltage, the net voltage in the primary circuit is zero. However, the changing current in the secondary circuit, due to the firing of the spark plug, indicates an additional voltage in the primary. This induced voltage is given by

$$\text{EMF} = -M(\Delta I_{secondary}/\Delta t)$$

Since the rate at which the secondary current decreases is constant, the induced EMF in the primary circuit is constant. The direction of this additional EMF is the same as the battery voltage, and the capacitor quickly becomes charged to a new voltage equal to the sum of the battery voltage and the induced EMF. The net voltage in the primary then becomes zero again.

INTERMEDIATE SECTION

When the spark plug stops firing, the current in the secondary is zero. As a result, the induced, constant EMF in the primary circuit disappears. When this happens, the capacitor suddenly has a higher voltage than the battery. The presence of this near-zero EMF in the primary causes the capacitor to discharge, which in turn sets up a decaying *L-R-C* oscillation, as previously discussed.

The intermediate section of the graph occurs between the time the secondary current drops to zero (spark plug stops firing)

and the re-closing of the points. For this oscillation, the inductance in the primary circuit is the self-inductance of the primary coil. Therefore, the period of oscillation in the intermediate section is given by the equation

$$T = 2\pi\sqrt{L_P C_P}$$

If one looks at the time required for this oscillation to decay to 36.8 percent of its initial maximum value, one can use that time and the resistance of the primary of the circuit to calculate the inductance of the primary coil. Use the equation

$$\tau_d = 2\ L_P/R_P$$

This value of L_P can be compared with the value we calculated using the L-R time constant when the points are closed.

These measurements and calculations may be applied to the ignition system by doing Experiment C-1.

CAUTION: High voltages are present in this experiment. Be careful not to touch the high voltage connections when the ignition switch is on.

1. With the points open, measure the resistance of the ballast resistor, R_B, and the primary coil, R_P. The sum of these two resistances is the total resistance of the primary circuit; the internal resistance of the battery is so small you may neglect it.

Connect the secondary of the ignition coil to the high voltage terminal of the spark-gap voltmeter.

2. Measure the resistance, R_r, of the 5-W resistor you have been provided and connect it between the low voltage terminal of the spark-gap voltmeter and ground. Measuring the resistor will give you a more precise value of its resistance than you could get by reading the color code.

Set the spark-gap voltmeter to approximately 5000 V. Connect the oscilloscope vertical input across the ballast resistor. Set the drive motor to slow speed and turn on the ignition switch. Adjust the oscilloscope to obtain a trace similar to Figure 46.

3. Measure the dwell time t_d, the firing time t_f, and the intermediate time t_i.

4. Measure the time required for the potential in the dwell section to go from 0 to 63 percent of V. This is the L-R time constant τ for the primary.

5. From the L-R time constant and the primary circuit resistance, calculate the inductance L_P of the primary.

$$L_P = \tau R$$

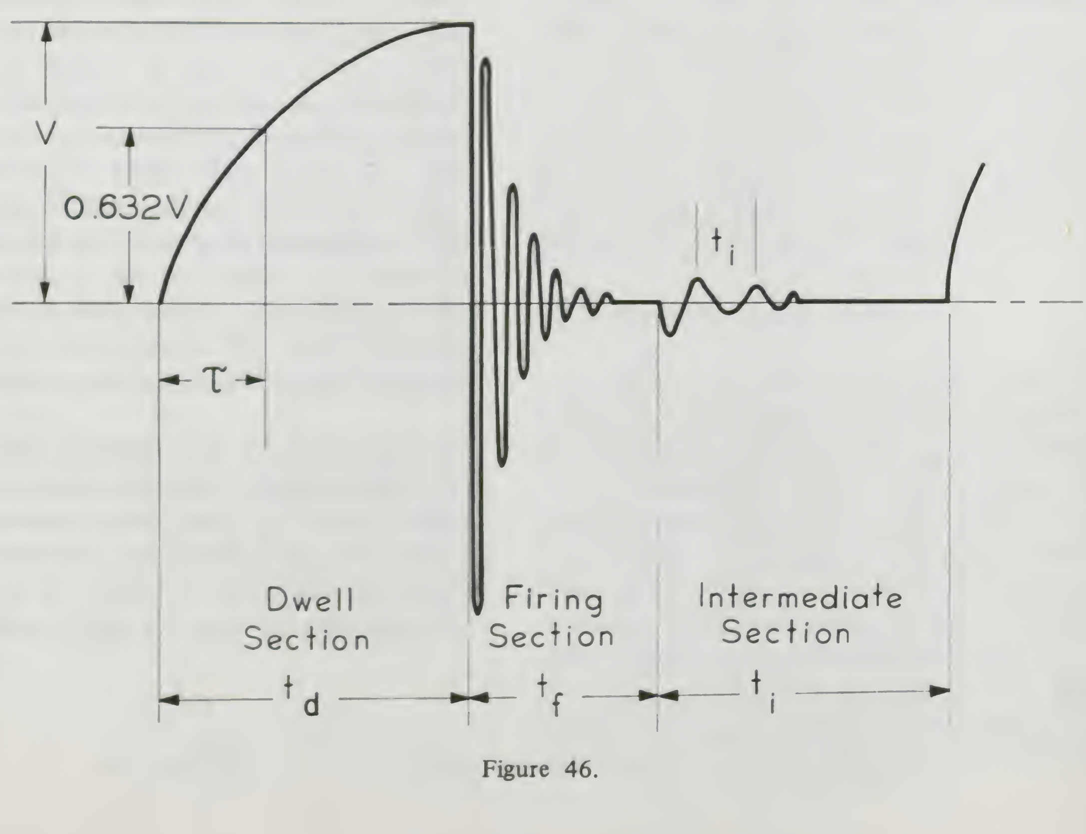

Figure 46.

6. Measure the period of oscillation T_i in the intermediate section. This oscillation is caused by the primary inductance L_P and capacitance C_P.

7. Using the equation

$$T = 2\pi\sqrt{L_P C_P}$$

and the value of L_P found in step 5, calculate the capacitance of the primary (C_P).

8. (Optional) If you can make the measurement, find the period of oscillation and the decay time for the oscillation in the firing section. Using $T = 2\pi\sqrt{L_{eff} C_P}$ and $\tau_{decay} = 2\ L_{eff}/R$, you can find out if there is a consistent value of effective inductance. You might also try to measure the decay time in the intermediate section to check the value of L_P using the relationship $\tau_{decay} = 2\ L_P/R$.

Turn off the ignition switch and put the vertical input of the oscilloscope across the primary coil. Turn on the ignition switch, run the distributor at slow speed, and adjust the oscilloscope to obtain a pattern similar to Figure 47.

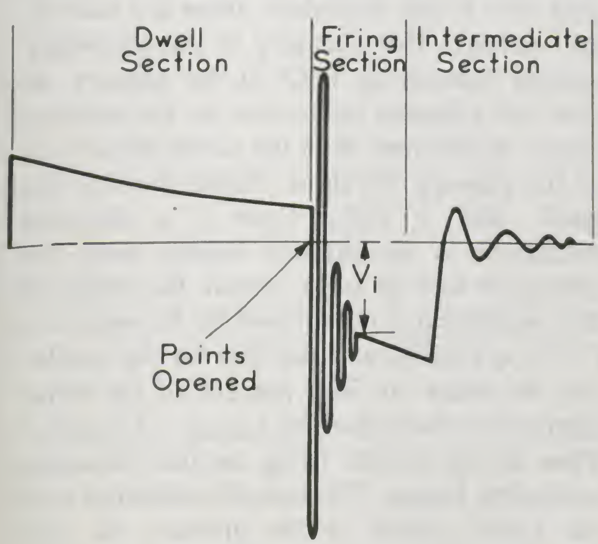

Figure 47.

9. During the firing section, the changing current through the secondary induces an average EMF, V_i, in the primary. Measure this induced EMF.

Turn off the ignition switch and put the vertical input of the oscilloscope across the resistor between the spark-gap voltmeter and ground. Turn on the ignition switch and adjust the oscilloscope to give a pattern similar to Figure 48.

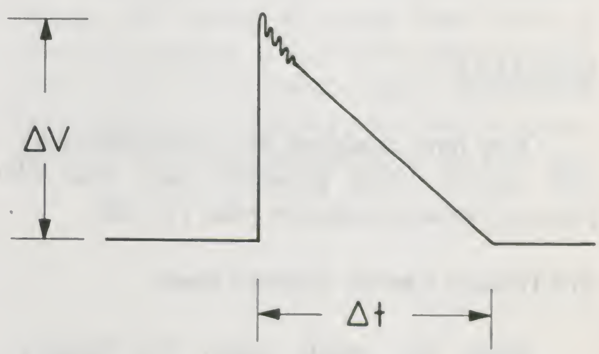

Figure 48.

10. Measure the time Δt required for the current through the spark-gap to drop from its maximum value to zero.

11. Measure the change in voltage ΔV across the resistor.

12. From Ohm's Law calculate the change in current ΔI through the secondary

$$\Delta I = \Delta V/R_r$$

13. As you have already learned, the induced EMF in the primary is related to the time rate of change of current in the secondary by the equation

$$V_i = -M(\Delta I/\Delta t)$$

where M is the mutual inductance.

Using your calculated value of ΔI and your measured value of Δt, calculate the mutual inductance, M.

14. The mutual inductance can also be calculated from the primary inductance (L_P) and the secondary inductance (L_S) by

$$M = \sqrt{L_P L_S}$$

The inductance of the secondary of an ignition coil is about 65 H. Use your value of L_P from step 5 to calculate M.

15. How do these two values of mutual inductance compare?

SUMMARY

You have analyzed the automobile ignition system using principles and laws of physics. Let us summarize what you did.

The Primary Circuit–Points Closed

When the points close, the primary circuit is completed and the current rises to its maximum value. By measuring the resistances of the primary coil and ballast resistor, you can use Ohm's Law to calculate the maximum primary current. (You could, instead, measure the maximum voltage and current and calculate the resistance.)

The current in the primary rises to its maximum value in a time interval which depends upon the inductance of the primary coil and the resistance of the primary circuit. The current rises to 63.2 percent of its maximum value in a time interval given by $\tau = L/R$. Using this equation, the measured time τ, and the resistance of the circuit, you determined the value of the inductance of the primary coil. You measured the time constant τ using an oscilloscope, when the scope was connected across the ballast resistor. At any given time, when the points are closed, the total EMF in the primary circuit is the battery voltage plus the induced EMF given by $V = -L(\Delta I/\Delta t)$. Thus you could calculate the induced EMF from this combination of *Faraday's Law* and *Lenz's Law* for a given time rate of change of current in the primary circuit.

The Primary Circuit–Points Open

When the points open, the primary current continues for a short time, charging the capacitor. The time required for charging this capacitor depends upon its capacitance and the total resistance in the primary circuit. The time constant of an *R-C* circuit is given by $\tau = RC$, so that you could measure the time required for the capacitor to charge to 63 percent of its maximum value, then calculate the capacitance. Connecting the oscilloscope across the points (and therefore across the capacitor) permits you to measure this *R-C* time constant.

When the points have opened, and the capacitor is fully charged, the current in the primary drops rapidly to zero. The situation is then rather complicated. Because the spark plug fires in the secondary, there is a secondary current. This changing in the secondary current induces an EMF in the primary, so that the effective inductance in the primary circuit is different from the actual inductance of the primary coil alone. During the time the spark plug is firing there is a *decaying oscillation* in the primary circuit. Since the primary is then an *L-R-C* circuit, the period of this oscillation is determined by the equation $T = 2\pi\sqrt{L_{eff}C_P}$, and the time for the oscillation to decay to 36.8 percent of its initial maximum value is given by $\tau_{decay} = 2\,L_{eff}R_P$. When the plug stops firing, another decaying oscillation begins. This second oscillation is in the *L-R-C* circuit of the primary, so that the period can be determined by using

$T = 2\pi\sqrt{L_P C_P}$ and the decay time by $\tau_d = 2\, L_P/R_P$.

Relationship of Primary and Secondary Circuits

During the time the spark plug fires, the primary and secondary circuits affect each other. When the points open and the primary current stops, there is a sudden collapse of magnetic flux through the coils. As a result, a very large voltage builds up across the spark plug gap. This high voltage breaks down the air gap and the spark begins. When you looked at the oscilloscope voltage trace across the small resistor in the secondary circuit, you saw a voltage "spike" followed by a uniformly decreasing voltage. The decreasing current induces through mutual induction an EMF in the primary coil. You calculated that induced EMF using the equation $V_P = -M(\Delta I_S/\Delta t)$. You saw this voltage on the oscilloscope trace when the scope was connected across the primary coil and the points were open. During the time the plug fires, this induced EMF shifts the trace of the first oscillation downward by an amount equal to the EMF. When the plug stops firing, this induced EMF stops, so the trace shifts back to the zero base line, and a new oscillation begins.

The ignition system is an excellent device with which to study basic laws of electromagnetism. If you wish, you may learn about some of the shortcomings of a conventional ignition system and what has been done to correct them by studying the next section.

TRANSISTORIZED IGNITION SYSTEM

The automobile ignition system has three major functions: (1) it supplies a spark to ignite the air-fuel mixture in the engine's cylinders; (2) it supplies this spark to each cylinder in the right order; and (3) it supplies the spark at the right time in the cycle to get the best use of the fuel. Over the years, the ignition system has been developed until it has become rugged and very reliable. It requires only occasional replacement of the points and spark plugs and adjustments of the distributor to keep it operating properly.

The conventional ignition system does have some shortcomings, and these are becoming of more concern as pollution control becomes more important. Some shortcomings are related to servicing convenience. We will now consider the major shortcomings and how transistorized ignition helps to overcome them.

For "clean" operation of an engine—that is, when the fuel is completely burned—the spark must have at least a certain amount of energy. (In the language of auto mechanics, it is a "hot" spark.) If it does not, the cylinder sometimes may not fire, or combustion may go poorly. Then fuel or partly burned gases (carbon monoxide) go out the exhaust. This situation causes poor gasoline mileage and adds to air pollution.

In normal low-speed operation, the ignition system can supply up to about 25,000 V, and this is enough to cause proper ignition. At high speeds, however, the dwell time is not long enough to allow the maximum current I_m to build up in the coil. Then, when the points open, there is only enough energy in the stored magnetic field of the coil to generate about 15,000 to 20,000 V. This lower voltage will not ensure that firing and fuel burning will be satisfactory. This is especially true when the plugs are fouled by deposits of lead oxides from the fuel. These deposits act as a resistance and reduce the power and voltage available for firing the plugs. It would appear that this problem could be overcome by using a ballast resistor of lower value, and by winding the coil primary with larger wire. This would make I_m higher and the current at high speeds would be higher. However, this current must go thorugh the points, and an increase much above 3 A to 4 A causes rapid destruction of points.

A transistorized ignition system solves this problem. In its simplest form, a transistor, instead of the points, is used as the switch for the primary current. Figure 49 shows a schematic of such a transistorized ignition system. Note that the points are still used, and they provide the necessary timing, but they now carry a much smaller current and control only the transistor. They do not carry the larger current of the primary circuit.

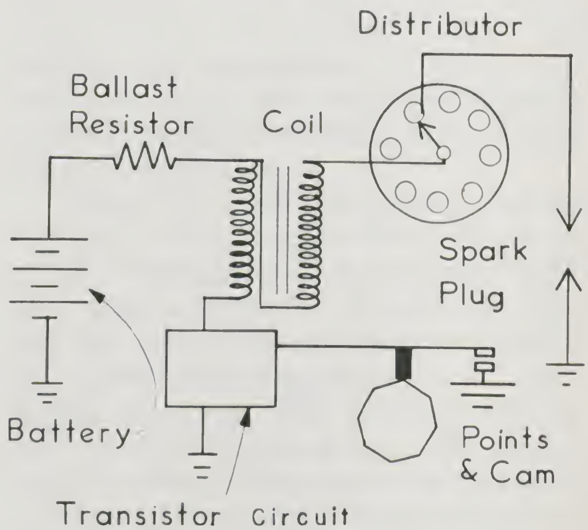

Figure 49.

Figure 50 shows the diagram, symbol, and a pictorial of a PNP transistor.

To better understand the transistor's operation, let's set up a simple analogy to a transistor. Its action can be compared to a water-flow system. The transistor is somewhat like a complicated valve, where a small current flowing through a small pipe controls a

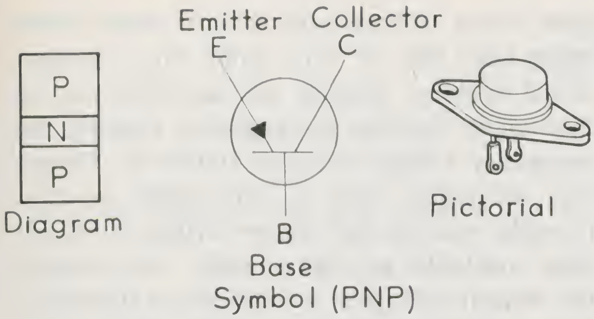

Figure 50.

large valve in a larger pipe. In the transistor, a small current flowing through the *base-emitter junction* can control a relatively large current flowing through the *collector-emittor junction.* This transistor operation is indicated in Figure 51.

A transistorized ignition system is designed to have very small currents through the points. Typically, if the primary current is to be 3 A, the base-emitter current then would be only about 0.15 A, and this is what the points would carry. This is a large reduction from the 3 A that the points carry in the conventional ignition system. It is so little, in fact, that arcing at the points is practically eliminated. No pitting or wear due to arcing occurs and the points last for much longer times. Adjustments and replacement are needed only as the anvil-and-hammer action of the points causes them to deform. Also, since the points carry so little current, the capacitor across them can be eliminated.

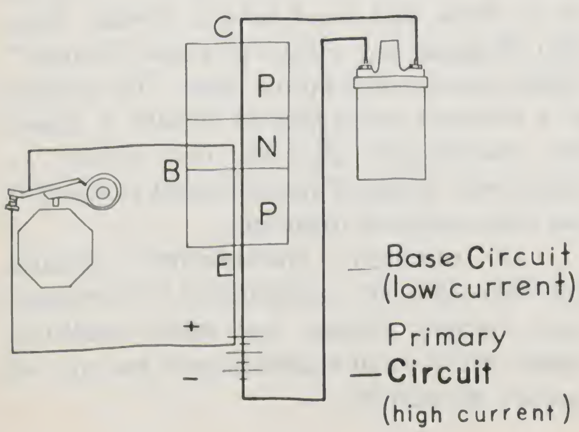

Figure 51.

When you studied the primary of the ignition system as an *L-R* circuit, the initial slope of the current versus time curve was given by the equation, initial slope = I_m/τ, where I_m was the maximum current and τ was the time constant. But you also used Ohm's Law to show that $I_m = V_B/R$, where V_B was the battery voltage and R was the primary circuit resistance. In addition it was pointed out that the time constant has a value given by the equation $\tau = L_P/R$, where L_P was the inductance of the primary coil. Using these latter two equations, the initial slope can be written as

$$\text{Initial slope} = (V_B/R)/(L_P/R)$$

$$= V_B/L_P$$

Thus the initial slope depends upon the inductance of the primary L_P and the battery voltage, but it does *not* depend upon the resistance. The maximum current depends upon the battery voltage and the resistance.

The problem in an ignition system is to get the primary current to rise to its maximum value within the dwell time for all engine speeds. For example, when an automobile is traveling at 70 mph, its engine may be turning at 3600 rpm. This corresponds to 60 rps, and since in an 8-cylinder engine there are 4 plug firings for each revolution, there will be 240 firings per second. The total time per firing is thus 1/240 s, and with a dwell of two-thirds the total time, the dwell time will be 2/3 X 1/240 = 0.0028 s or 2.8 ms. At 35 mph, the engine speed is 2200 rpm, and the dwell time is 4.6 ms.

A regular ignition system primary coil has an inductance of about 7.5 mH and a primary circuit resistance of about 3 ohms. The time constant is therefore about $(7.5 \times 10^{-3})/3$ seconds, or about 2.5 ms. Thus, at 70 mph, the dwell time is smaller than the time constant, and the current cannot reach its maximum value. At 35 mph, the dwell time is almost twice as long as the time constant, so the current will nearly reach its maximum value.

This means that less magnetic flux is available to collapse and produce spark at higher speeds, so the spark is weaker.

This problem can be corrected by increasing the slope of the current-time curve for the primary circuit, or by increasing the maximum current in the primary circuit. Since the initial slope is given by V_B/L_P, the current can be made to rise more quickly by *decreasing* the inductance of the primary coil. The maximum primary current can be increased by decreasing the primary coil resistance. If a transistor is used to control the primary current we can increase the current because the points no longer carry this current. There is no need to worry about damage to the points from the larger currents.

The earlier models of transistorized ignition systems used a special coil. The inductance was reduced to about 1.3 mH and the resistance was reduced so that the primary circuit resistance was only about 1.3 Ω. Then the time constant is about 1 ms, and even at 70 mph, the dwell time is over twice as long as the time constant. The current therefore has plenty of time to build up to its maximum value, and the spark voltage is high for all driving speeds.

The simple transistor system which we have considered so far requires a special coil and a transistor that can handle high currents. In recent years, a different transistorized system has become popular. This system uses a standard coil and smaller transistors. The system is known as a *capacitor-discharge system.* In this system, a transistorized "chopper" breaks the d-c current from the battery into 12-V pulses, and these are converted by a transformer into 300-V alternating current. This alternating current is rectified to give 400-V direct current, which charges a capacitor. At the correct times, as controlled by the opening of the points, a transistor switch allows the capacitor to discharge through the coil primary. In this way, the coil generates up to 40,000 V at the secondary.

The initial slope of the primary coil current-time graph is now 400 V/L_P, which, even for a conventional coil, is much more steep than the 12 V/L_P slope for a conventional system. Because the capacitor can be discharged through the coil very rapidly, the secondary voltage reaches 40,000 V. Capacitor recharging time is very small, so that it easily reaches full charge within the dwell time available at high speeds. As a result, the output voltage is maintained at all speeds. The switching transistor must withstand a fairly high voltage, but the current which it handles is not large.

Although the transistor switch solves the problem of point erosion, the transistor still is controlled by the opening of the points. Any lack of perfection in the parts of the distributor will still lead to uneven timing between firings. The sensitivity of transistor switches can be made high enough so that they will respond to other signals, and this is made use of in some transistorized ignition systems. In one class of these systems, an eight-armed rotor is attached to the distributor shaft and the points are replaced by a coil of wire wound on a magnetic pole-piece. As the rotor arms pass by the pole-piece, the changing magnetic field induces a current pulse in the coil, and this pulse triggers the transistor ignition. In another class of such systems, a light beam between a small lamp (or light-emitting diode) and a photocell is interrupted by a disc on the distributor shaft. When one of the eight holes in this disc allows light to pass to the photocell, a pulse is generated which triggers the transistor ignition. Since there are no points in these systems, there can be no wear, and the timing is precise. They also eliminate any effects of point "bounce," which occurs when points close. This bounce is a rebound and a second closure at about one microsecond after the first closure. In improperly designed transistorized systems, it can cause multiple triggering.

In summary, transistorized ignition systems can make adjustments for temperature, battery voltage, and other conditions which affect engine performance and are not usually allowed for.

Work Sheets
EXPERIMENT A-1

Name____________________

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7. ____________________
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COMPUTATION SHEET

Work Sheets
EXPERIMENT A-2

Name________________________

Part I. Magnetism

1. ______________________________
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Part II. Electromagnetism

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19. ____________________
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Work Sheets
EXPERIMENT B-1

Name ____________________

1. t_1 = ____________________

   t_2 = ____________________

2. V = ____________________

3. R_1 = ____________________

4. I = ____________________

5.

6. ____________________

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   ____

7. ____________________

   ____

8. ____________________

9. τ = ____________________

10.

11. ____________________

    ____

    ____

    ____

12. τ = ____________________

13.

14. ____________________

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    ____

15. t = ____________________

16.

17. t = ____________________

18.

20.

19. ____________________________

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21. ____________________________

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Work Sheets
EXPERIMENT B-2

Name________________________

1. ________________________V

2. ________________________V

3. ________________________Ω

4–6.

V_1 (V)	V_s (V)	I_p (A)

8. ________________________

9. ________________________

10. ________________________

11. ________________________

COMPUTATION SHEET

Work Sheets
EXPERIMENT C-1

Name____________________

1. R_B = ____________________ Ω

   R_P = ____________________ Ω

   $R = R_B + R_P$ = ________________ Ω

2. R_r = ____________________ Ω

3. t_d = ____________________ s

   t_f = ____________________ s

   t_i = ____________________ s

4. τ = ____________________ s

5. L_P = ____________________ H

6. T_i = ____________________ s

7. C_P = ____________________ F

8. T (firing) = ________________ s

   L_{eff} = ____________________ H

   τ_{decay} = __________________ s

   L_{eff} = ____________________ H

   τ_{decay} (intermediate) = ____________ s

   L_P = ____________________ H

9. V_i = ____________________ V

10. Δt = ____________________ s

11. ΔV = ____________________ V

12. ΔI = ____________________ A

13. M = ____________________ H

14. M = ____________________ H

15. ________________________

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APPENDIX: The Oscilloscope

The oscilloscope is nothing more than a very fast "graphic machine". It is able to present graphs of voltages (usually on the vertical axis) against time or other voltages (on the horizontal axis). Thus the scope displays the size, shape, and frequency of an input signal. How the oscilloscope circuits are designed is not important for this module. Instead, we shall examine the functions of the external controls which are common to most general-purpose laboratory oscilloscopes. Because most oscilloscopes have additional features and because the naming of controls varies among oscilloscopes, the operating instructions for a specific oscilloscope should always be consulted before use. (The terms scope and oscilloscope are used interchangeably here.)

Some of the basic controls found on all oscilloscopes are listed below, along with a brief explanation of their functions. As you read the description of each control, you should refer to the one on your scope.

I. Screen Section

A. The AC ON/OFF control turns the oscilloscope on. It is usually combined with either the INTENSITY control or the SCALE ILLUMINATION control. Most scopes have a panel light to indicate when they are on.

B. The INTENSITY control changes the brightness of the spot (or trace). If a bright spot is left in one place on the screen for too long, it can "burn" away the phosphor on the screen, leaving a permanent dark spot. For this reason, the intensity is usually kept as low as is consistent with good viewing.

C. The FOCUS control adjusts the sharpness of the trace. It should be adjusted to give the narrowest line possible.

D. The VERTICAL and HORIZONTAL POSITION controls change the up-down and left-right positions of the beam. On some scopes, you may find a BEAM FINDER button, which allows immediate location of a beam which is "off the screen." After finding the beam with the beam finder, you can then use the positioning controls to move the beam to the center of the screen.

II. Vertical Amplifier Section

E. The voltage to be analyzed is usually connected to the VERTICAL INPUT. If there is a *probe* provided with the scope, be sure to check its *attenuation factor.* Most probes are designed to reduce the voltage input to the scope by a factor of ten or more. Any calculation of voltage should include this factor.

F. The VOLTS/CM (also called VERTICAL SENSITIVITY) control allows measurement of the size of a voltage signal. The face of most oscilloscope screens is covered with a grid which is ruled in centimeters. This grid is used to read the voltage of a signal. For example, suppose the trace is 2.5 cm high and the VOLT/DIV is set on 10 VOLTS/CM. Then the voltage input to the scope is 2.5 cm X 10 VOLTS/CM or 25 V. (On many scopes, a concentric control knob allows the vertical sensitivity to vary. For calibrated readings this knob must be properly set.)

III. Time Base Section

G. The TIME/CM control (also called the SWEEP RANGE SELECTOR) varies the rate at which the trace "sweeps" across the oscilloscope screen. This feature is necessary to

allow measurement of the duration of a signal or of the frequency of the signal. For example, if a voltage pulse is 4 cm long and the TIME/CM switch is set on 20 ms/cm, the time required for the pulse is 4 cm X 20 ms/cm or 80 ms. (On many scopes a *multiplier* switch allows the calibration time to be changed by some factor.)

H. A SYNC (synchronization) control is part of the time base section on many inexpensive scopes. Its purpose is to cause the sweep voltage to always begin at the same point of a recurrent signal, so the signal appears to "stand still." The SYNC control is turned until the pattern on the screen appears stationary. If you cannot "stop" the signal, you may beed to choose a different sweep rate.

I. The SYNC SELECTOR control selects one of three possible *modes of synchronization.* On INTERNAL SYNC, the input is synchronized with the internal sweep of the scope. On EXTERNAL SYNC, the input is synchronized with an external signal; on LINE SYNC, the input is synchronized with the AC line voltage. This control is usually set to INTERNAL.

J. On more sophisticated scopes, the TRIGGER controls achieve synchronization. Triggering means that the horizontal sweep is caused to begin (triggered) whenever the input signal reaches a predetermined value.

The following exercise is to acquaint you with the controls of the oscilloscope you will use in the *Automobile Ignition System* module. You will need to consult the operating manual for your scope. If you have problems, consult your instructor.

LABORATORY EXERCISE

1. With the power off, examine the scope and locate the following controls or their equivalents.

   a. INTENSITY

   b. FOCUS

   c. VERTICAL INPUT TERMINALS

   d. VOLT/CM

   e. TIME/CM

   f. SYNC controls or

   g. TRIGGER controls

2. a. Find out, from the operating manual, how to turn off the internal sweep. This may be done by setting the TRIGGER LEVEL to a high position, or by turning the sweep selector to external (with no external input signal).

   b. Turn the FOCUS and INTENSITY controls fully counterclockwise.

   c. Set the VERTICAL and HORIZONTAL POSITION controls to the midpoints of their positions.

   d. Turn on the scope and allow it to warm up for at least one minute.

   e. Turn up the intensity until you see a spot on the screen. Do not turn the intensity higher than you need to. A glow around the spot indicates a too-high intensity. If no spot is visible, it is probably "off-screen." Use the positioning controls to move the spot onto the screen.

   f. Rotate the FOCUS control to see the effect, and adjust to get a very small bright dot on the screen.

g. Observe the effects of the HORIZONTAL and VERTICAL position controls and center the dot.

h. Set the SWEEP selector to an internal sweep and turn on a recurrent sweep. You will need to consult the operating instructions.

i. Observe the effect of changing the TIME/CM setting. Expand the dot into a line by increasing the sweep rate.

3. You are now ready to observe an input signal.

a. Connect the voltage output of a sine and square-wave generator to the vertical input of the scope. Connect the ground terminal of the generator to the ground input of the scope.

b. If you have a triggered scope, set the TRIGGER to "auto." If the scope is not triggered, set the SYNC selector to INTERNAL.

c. Set the TIME/CM switch to the slowest sweep rate (on the order of 1 s/cm). (Make sure the vertical is set for *calibrated* measurements.)

d. Set the generator to give a sine wave with a frequency of 1000 Hz. Turn on the generator.

e. Adjust the generator output (and/or VOLTS/CM control) to obtain a signal which is about 5 cm high.

f. Observe the effect of increasing the sweep rate.

g. Observe the effect of varying the frequency of the input signal.

h. Change the output of the generator to "square wave" and observe the pattern.

i. If you have a triggered scope, set the TRIGGER to INTERNAL. Adjust the TRIGGER LEVEL control until you get a stable trace which "stands still." Center the trace.

j. Measure the length of a single pattern on the screen and use the TIME/CM setting to compute the duration of the pattern. How does your measured value compare with the value computed from the known input frequency? (Be sure the *multiplier* is set to 1, or that you include the proper factor.)

k. Change the input frequency and repeat (i) and (j).

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